Energy Research and Development Division
FINAL PROJECT REPORT

ENERGY EFFICIENCY IN WATER REUSE AND DESALINATION

Five Individual Projects Which Address Energy Efficiency in both Water Reuse and Desalination

Appendices

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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ABSTRACT

Water reuse and desalination are potential solutions to help meet the water demands of a growing population in states such as California. However, water reuse and desalination systems are energy intensive processes. This is of particular concern due to the rising costs of electricity and pollution concerns. The California Energy Commission and the WateReuse Research Foundation have joined forces to support five projects that identify opportunities to reduce energy demand.

The five projects covered three study areas:

1. Opportunities for new water sources in the energy industry,
2. Optimizing water reuse and desalination systems, and
3. Using water reuse and desalination to prepare for climate change.

The first study area explored opportunities that show high potential for water reuse as a new water source in the energy industry. A background report exploring this question thoroughly and a decision support tool were developed to bridge the gap between water reuse and energy industries. The results of the study show that there is great opportunity for water reuse in the energy industry; however the power and heat production sector has the most potential.

The second area explored was system optimization. In one study, a guidance manual with strategies for energy minimization and promotion of alternative energies was developed for water reuse and desalination utilities. Another study in this topic area focused specifically on energy recovery devices (ERD) for desalination and wastewater membrane plants. A model was created to assist water utilities in assessing whether an ERD is appropriate (i.e., cost effective) for a reverse osmosis (RO) application and, if so, to select the most appropriate ERD for the specific application.

The third topic area explored was the potential of using water reuse and desalination as part of the solution for climate change. In one study under this area, a guidance document was produced to direct water utilities in long- and short-term planning for climate change with a focus on water reuse. In a second study under this area, a computer model called WESim was also developed, allowing water utilities to integrate a theoretical water reuse or desalination system into their current water portfolio to determine if it is a prudent alternative from an energy and carbon use perspective.

Keywords: Water reuse, energy efficiency, ERD, desalination, energy minimization, alternative energy, biofuels, climate change

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APPENDIX A:
Requirements and Opportunities for Water Reuse in Energy and Biofuels

Requirements and Opportunities for Water Reuse in Energy and Biofuels

About the WateReuse Research Foundation

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

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

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

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Acronyms

AOP	advanced oxidation processes
BEPP	bioenergy processing and production
BFPP	biofuels processing and production
BMFP	biomass feedstock production
BOD	biological oxygen demand
CCS	carbon capture and storage
CEC	California Energy Commission
CHP	combined heat and power
COD	chemical oxygen demand
CSP	concentrating solar power
DDSD	Delta Diablo Sanitation District
DEC	Delta Energy Center
DOE	Department of Energy
EC_w	electrical conductivity of water
EDR	electrodialysis reversal
EERE	energy efficiency and renewable energy
EGS	enhanced geothermal system
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
FAME	fatty acid methyl esters
FOG	fats, oils, and greases
F-T	Fischer-Tropsch
GUI	graphical user interface
IDEA	International District Energy Association
IGCC	integrated gasification combined cycle
LMEC	Los Medanos Energy Center
MF	microfiltration
MRWPCA	Monterey Regional Water Pollution Control Agency
MSW	municipal solid waste
MWRSA	Monterey Wastewater Reclamation Study for Agriculture
NCPA	Northern California Power Agency
NGCC	natural gas combined cycle
O&M	operations and maintenance
PBR	photobioreactor
PHP	power and heat production
PV	photovoltaic
RGGI	Regional Greenhouse Gas Initiative
RO	reverse osmosis

RWF	recycled water facility
SWRCB	State Water Resources Control Board
SWWTF	Seeley Wastewater Treatment Facility
TAG	triglyceride
TDS	total dissolved solids
TSS	total suspended solids
UF	ultrafiltration
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
U.S. EPA	United States Environmental Protection Agency
UV	ultraviolet
WCI	Western Climate Initiative
WSWPCF	White Slough Water Pollution Control Facility
ZLD	zero liquid discharge

Foreword

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

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

- Defining and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

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

This study examines the potential opportunities for recycled water use within the energy and biofuels–related industries. The report gives a summary of the industries covered by the study, identifies potential recycled water demands, water quality requirements, and describes the primary issues and barriers to using recycled water in these industries. Finally, the report describes a Web-based Decision Support Tool that will be used to introduce the recycled water industry to the industries of energy and biofuels to facilitate future recycled water projects.

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Executive Summary

The purpose of this report is to connect the recycled water and energy and biofuels industries and assess and characterize the potential for water reuse in the following four energy sectors:

- **Power and heat production (PHP)**. Includes traditional, large-scale power generation (coal, natural gas, oil, nuclear) in addition to renewable energy–fueled power generation methods that use large amounts of water, such as concentrating solar power (CSP) and geothermal.
- **Biofuel processing and production (BFPP)**. Includes biofuel production industries, such as ethanol and biodiesel.
- **Bioenergy processing and production (BEPP)**. Includes the use of biomass as fuel for producing electricity. Methods include co-firing, pyrolysis, and anaerobic digestion, among others.
- **Biomass feedstock production (BMFP)**. Includes the production of any biologically based material that can be used as feedstock for biofuels or directly as fuel for making energy. Biomass includes agricultural crops, residues, woody wastes, and municipal wastes, among others.

The objectives of the study include the following:

1. Identify and quantify potential recycled water markets and demands in each of the four energy sectors.
2. Characterize the water quality requirements for these water demands and suggest treatment methods to meet those requirements.
3. Compile issues and barriers that may hinder the use of recycled water.
4. Develop strategies to enhance the use of recycled water in the four energy sectors.
5. Create a decision support tool to guide recycled water users and suppliers to meet the potential demands identified in this study for recycled water.

The intended audience for this report includes members of the recycled water industry interested in learning about new industrial and agricultural recycled water demands in these emerging fields as well as people working in the industries that compose the four energy sectors. Those readers from the four energy sectors may not know the basics of recycled water, and so the report includes an overview of recycled water treatment, typical water quality, and case studies in which recycled water has been successfully used in applications similar to those that exist in the four energy sectors.

Water Demand Quantity

This study confirmed that substantial quantities of the water demands in the four energy sectors can be met by recycled water use. Cooling tower make-up for wet recirculating cooling towers is the largest potential demand across the PHP, BEPP, and BFPP sectors.

Boiler feed is also required in the PHP, BEPP, and BFPP sectors, and under the right circumstances that demand could be met with recycled water.

The study found that the largest potential quantity of recycled water could be utilized in the PHP sector. Power generation is expected to increase steadily for the foreseeable future, requiring new power plants that could potentially use recycled water. In addition, many existing power plants are scheduled to be retired as they reach the end of their useful lives, requiring replacement. These demands are nearly certain to occur, the only uncertainty being the timing of project implementation and the potential use of dry cooling (air-cooled condensers) technology, negating the need for cooling tower make-up water.

Water Quality Requirements

Typical tertiary-treated recycled water can be utilized as is for cooling tower make-up water. Projects need a specific technological assessment to determine if an existing source of recycled water needs additional treatment. For cooling tower water, the constituents that typically drive the selection of a water supply or the need for additional treatment include total dissolved solids (TDS), ammonia, silica, alkalinity (and associated constituents like calcium and magnesium), phosphate, and metals.

Boiler feed, slurry water for ethanol production, and other process water used in the four energy sectors typically require higher treatment in the form of membrane filtration, reverse osmosis, or some other type of demineralization or desalination treatment. The constituents that drive selection of water supply or the need for additional treatment include TDS, silica, metals, turbidity, and pH, all to levels that cannot be met with traditional tertiary treatment.

Irrigation water quality requirements vary according to the specific crop, but general guidelines suggest that the constituents that drive suitability of a recycled water supply with irrigation include salinity (e.g., TDS and EC_w), chloride, sodium, and boron, although other constituents can also limit the use of recycled water, including metals. Recycled water can sometimes provide an additional nutrient benefit if nitrogen has not been removed from the water during wastewater treatment.

Recycled Water Opportunities in the Four Energy Sectors

The results of the study identified many potential recycled water demands in the four energy sectors. Figure ES.1 illustrates an estimate of the potential magnitude of the demands identified in this study, with estimates of the time frame of implementation and the relative likelihood that these types of demands will be met with recycled water. The bubbles in the upper right quadrant of the graph have the most potential in the near term, so these should be targets of recycled water suppliers. Many of the industries covered by this study include technologies and products that have not yet been established widely in the commercial markets, such as cellulosic ethanol production, cultivation of algae, and gasification of biomass for power production. Because these industries are relatively new, there is a high level of uncertainty in both the time frame estimates and the scale of the water demands, as those water demands will depend largely on the success of the new technologies. Even with these uncertainties, it’s helpful to make these estimates in order to target the most likely demands available to be met by recycled water.

As presented in Figure ES.1, PHP has the largest potential demands relative to the other energy sectors, with BMFP following as the next largest set of demands. This result is

expected, as the power industry and agricultural irrigation have the largest fresh water demands in the United States. Within PHP, carbon capture and sequestration (CCS) also has a substantial potential for water demands, as it would require additional power capacity. Biofuels production has a much smaller water demand relative to these other demands on an industrywide basis; however, there are likely still opportunities for recycled water use because new plants are expected to be built as biofuels use expands. New facilities are the best opportunities for recycled water implementation projects because facilities can be designed specifically for recycled water.

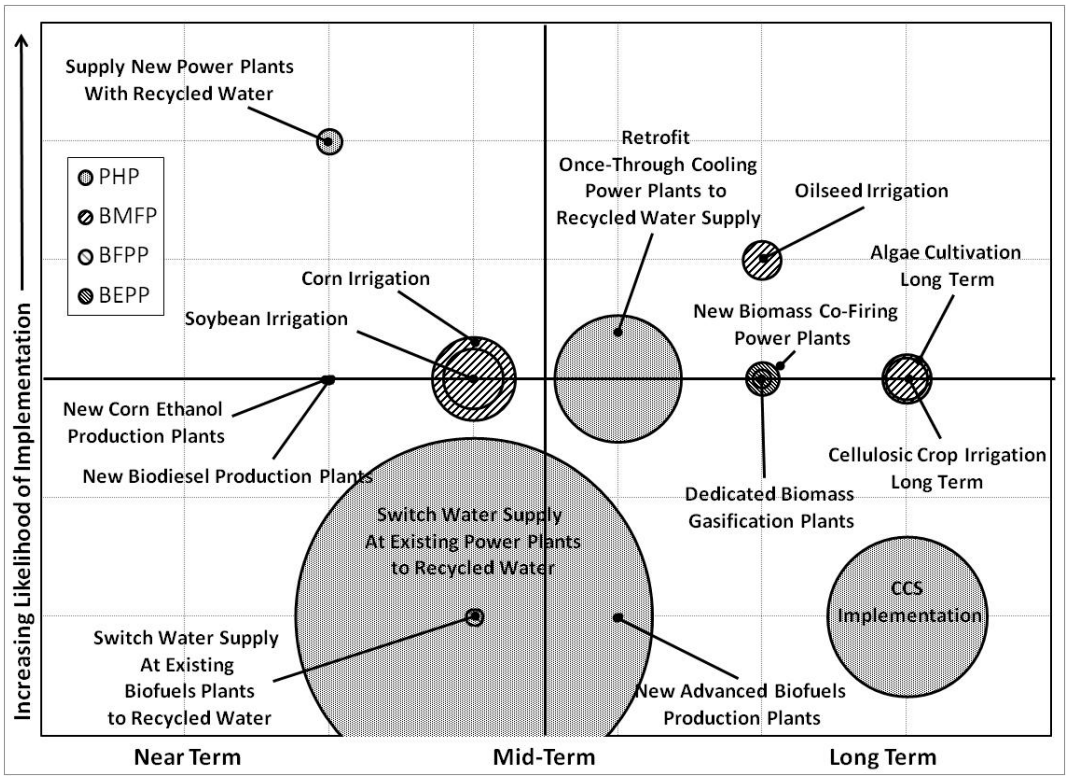

Figure ES.1. Relative opportunities for recycled water in the four energy sectors.

Issues and Barriers to Recycled Water Use

The issues and barriers associated with implementation of recycled water projects in the four energy sectors are generally in line with typical requirements in any recycled water implementation project, although there are specific considerations needed. These issues and barriers include

1. **Cost and supply availability considerations.** For successful implementation of recycled water projects in the four energy sectors, cost of that supply is often the primary consideration for potential users along with the reliability of that supply, as these industries are highly competitive and have low profit margins. The cost of recycled water must therefore be minimized to make it attractive to these potential users, and to do that it helps for both the potential user and recycled water supplier to collaborate early on in the project development to identify the technical requirements

and analyze the low-cost alternative. In addition, the reliability of recycled water supplies is a key benefit relative to weather-dependent potable water supplies.1.

2. **Outreach to potential users.** One barrier to project implementation is the lack of knowledge recycled water suppliers and potential users in the four energy sectors have of each other. One goal of this study is to improve awareness across these two industries, which should increase the number of recycled water projects in these sectors. For suppliers, outreach involves monitoring plans for new facilities in their area and getting involved by providing input during public commenting periods of the project approval process.

3. **Market uncertainty**. Many of the technologies and products included in the four energy sectors have not yet been established commercially. Those that have will grow depending on uncertain factors, such as government incentives. In particular, industries such as cellulosic biofuels and feedstock production, cultivation and use of algae as a biomass feedstock, and biomass gasification all have great potential, but projections for many of these industries have been overly optimistic in the past, and research and development are ongoing.

4. **Regulatory issues**. Regulations for projects in the four energy sectors are similar to existing projects with industrial and agricultural users, so the experiences and examples of success exist to guide projects in these areas. The challenge will be for states without established regulations that have a large potential for recycled water use in the four energy sectors, such as the corn-growing states of the Midwest. Projects must meet regulations for recycled water treatment and permitting, environmental documentation, water rights, and discharge.

5. **Institutional issues and arrangements**. A key to a successful, long-term arrangement between a recycled water supplier and user is an agreement that establishes guarantees for level of service, water supply quantity, rates, water quality, and other responsibilities. These agreements are typically called a water purchase agreement but can come in many other forms. Successful agreements are typically specific and delineate responsibilities for operations and maintenance, reliability, water quality requirements, regulatory reporting and other requirements, rates, and term of the agreement.

6. **Public acceptance, support and outreach**. Compared to other recycled water projects where the public is more likely to come into contact with recycled water use, such as landscape irrigation of parks, public acceptance has not been as much of a problem for industrial and nonfood crop agricultural users. Industrial use of recycled water is typically seen as preferable to using potable water sources, and so the public generally does not oppose projects offsetting the use of potable supplies to reserve those supplies for residential use. Agricultural irrigation for biomass feedstocks even has an advantage over food crops (which have been irrigated with recycled water for years) in that the crops are not for human consumption.

Decision Support Tool

The effort to bridge the gap between the recycled water industry and those in the four energy sectors in the study involved the development of a Decision Support Tool that can be used by people coming from either perspective to learn more about whether recycled water is right for

a particular project. The tool is a Web-based interface that uses Google Maps code to display information about potential users, including power plant locations, existing and proposed biofuels production facilities, resource information, and wastewater treatment facility locations (i.e., sources of recycled water supply). The tool is available at the following link: http://reuse-energy-biofuels.rmcwater.com

The objective of the tool is to provide guidance for both recycled water suppliers and potential users in the four energy sectors. The intent is to create a planning level screening tool to provide both quantitative and qualitative guidance to the user as to whether recycled water will work in a particular situation. The guidance provided will include suggestions for the most likely level of treatment, conveyance facilities, potential demands, water quality requirements, and other project considerations that may influence the decision to use recycled water. The tool is Web based to take advantage of the readily available mapping application programming interface from Google Maps.

Recycled water suppliers can introduce themselves to users in the four energy sectors by using the tool to

- Select water demands that can be met by the supplier's recycled water, given the available supply and typical water quality of that water.
- Learn the typical water quality requirements for users in each energy sector, as well as about the associated reliability and operational requirements.
- Understand the typical process for developing a recycled water purchase agreement with users from the four energy sectors and what types of concerns and requirements would be included in such agreements.
- Display locations of select potential users, including power plants, biofuels production facilities, and bioenergy facilities.

Potential recycled water users from the four energy sectors will be able to

- Identify potential recycled water suppliers near their facility's location, with estimates of potential recycled water capacity and, in some cases, supply availability.
- Input their water quality requirements to compare typical or expected recycled water quality.
- Identify the level of treatment needed to get the water quality they require.
- Receive guidance on the need for public outreach and successful strategies from similar projects.

Recommendations

With the goal of increasing collaboration between the recycled water industry and the four energy sectors defined by this project, we offer the following recommendations for those interested in pursuing potential recycled water projects within the four energy sectors.

1. **Target projects where user is close to the supplier.** The projects most likely to be cost-effective for both the recycled water supplier and user are those where the source of

water is close to the point of use. If distribution infrastructure and power are required to convey recycled water to the use site, the costs can make the project less attractive.

2. **Target new facilities.** Use of recycled water in many of the uses highlighted in this study requires either equipment suited to the water quality of recycled water or additional treatment. Designing a facility and selecting equipment with recycled water specifically in mind avoids the need for costly retrofits, as may be required for existing facilities.

3. **Partner with regulators**. Recycled water suppliers should collaborate with regulatory agencies regarding the use of recycled water for new projects as a way to promote recycled water, increase awareness of recycled water for both the regulators and project representatives, and learn about potential projects in their area. Partnering agencies may increase the likelihood that agencies will emphasize the need to utilize recycled water rather than other supplies because they review the project for approval and will educate applicants about the benefits of recycled water.

4. **Use existing experience as guidance for future projects**. Despite the fact that many of the industries in the four energy sectors involve new, emerging technologies, the water demands that offer the largest potential quantities, including cooling tower make-up, boiler feed, and irrigation, all have existing, established facilities with success using recycled water that can serve as examples for future projects.

Chapter 1

Introduction

For decades, research and development has been ongoing to replace traditional fossil fuels with alternative fuels and renewable energy sources. Energy crises and cost spikes have motivated the switch from petroleum-based transportation fuels, while increasing demand and concerns over pollution and climate change guide businesses and researchers to look for new sources of power generation. Following a slight drop in overall energy use in 2008–2009 due to recession, overall energy consumption in the United States is expected to jump by approximately 7% in the next 10 years, while hundreds of megawatts of electricity-generating facilities are scheduled to be shut down for replacement (U.S. EIA, 2011a). Oil prices have rebounded since the recession but continue to fluctuate because of continued uncertain economic conditions, natural and manmade disasters, and turmoil in oil-producing countries. The process of finding new energy supplies to replace the traditional sources has accelerated in recent years as technology improves and these drivers increase pressure to find alternatives. A world economy that relies less on traditional fossil fuels and more on alternative fuels is becoming reality.

In parallel to this transformative process of broadening our sources of energy, governments, researchers, and businesses have recognized that energy has a strong relationship with water, compelling them to consider both when planning. This applies as much to traditional technologies and fuels as it does to emerging and alternative technologies. The interrelationship between water and energy has become known as the Water–Energy Nexus. Power generation and fuel production require large quantities of water. Treatment and conveyance of water and wastewater require substantial amounts of energy, although some can be offset by wastewater treatment, which can include a process to increase energy production. As energy demands grow and water becomes scarcer, this interdependency becomes more influential in determining the appropriate steps needed to meet future demands for both energy and water.

With the movement toward new energy sources, planners must consider the impact to water resources and develop strategies for meeting the associated water demands. Recycled water exists as a valuable resource to replace traditional potable and surface waters that should be reserved for other beneficial uses. This study is intended to bring the worlds of energy and biofuels together through the water reuse industry to identify opportunities in which recycled water can be used to meet the growing water demands in the many established and burgeoning industries related to energy. It will focus on four energy sectors covering a wide array of technologies and industries and identify how recycled water use can be expanded or established in each of those sectors. The study will address common and unique water uses and assess how the recycled water industry is positioned to supply these uses.

1.1 Purpose and Objectives

The purpose of this report is to connect the recycled water and the energy and biofuels industries in order to promote recycled water use in areas that stand to benefit from an alternative water supply. To accomplish this goal, this report introduces the concept of recycled water and assesses and characterizes the potential for water reuse in the following four energy sectors:

- **Power and heat production (PHP)**. Includes traditional, large-scale power generation (coal, natural gas, oil, nuclear) in addition to renewable energy–fueled power generation methods that use large amounts of water, such as concentrating solar power (CSP) and geothermal.
- **Biofuel processing and production (BFPP)**. Includes biofuel production industries, such as ethanol and biodiesel.
- **Bioenergy processing and production (BEPP)**. Includes the use of biomass as fuel for producing electricity. Methods include co-firing, pyrolysis, and anaerobic digestion, among others.
- **Biomass feedstock production (BMFP)**. Includes the production of any biologically based material that can be used as feedstock for biofuels or directly as fuel for making energy. Biomass includes agricultural crops, residues, woody wastes, and municipal wastes, among others.

This study is intended for potential users of recycled water in these energy sectors, as an introduction to recycled water and how it could meet their demands, and for existing or potential suppliers of recycled water, to identify potential new demands that can be met with their recycled water.

The objectives of the study include the following:

1. Identify and quantify potential recycled water markets and demands in each of the four energy sectors
2. Characterize the water quality requirements for these water demands
3. Compile issues and barriers that may hinder the use of recycled water
4. Develop strategies to enhance the use of recycled water in the four energy sectors
5. Create a decision support tool to guide recycled water users and suppliers to meet the potential demands identified in this study with recycled water

The intended audience for this study includes

- **Recycled water suppliers**. The water reuse industry as a whole has much experience with recycled water use in industrial and irrigation applications. The industries covered by this study offer potential new markets. This study offers an introduction to these new markets for recycled water suppliers. Often, recycled water suppliers seek several large "anchor customers" who assure a large demand component and a consistent revenue supply, enabling the recycled water supplier to invest in treatment, delivery, and distribution infrastructure, which can then be used to meet additional, smaller but highly valuable, demands (such as landscape irrigation) along the pipeline route. Users in the four energy sectors offer opportunities for new anchor customers that could provide steady, nonseasonal demands that would allow for full utilization of the suppliers' recycled water supply.

- **Water users from the four energy sectors**. This study provides an introduction to water reuse for potential users from a perspective tailored to the four energy sectors. Much of the Industry Assessment may not be new to these readers, but it will help to connect them and their concerns with the recycled water production industry.

Chapter 4, Issues and Barriers, covers more directly the considerations and concerns that users may have in selecting recycled water for their water supply.

1.2 Scope of Study

The scope of this study includes the issues of water supply and demand in the four energy sectors; more specifically, it identifies opportunities for meeting these sectors' demands with recycled water. This study recognizes that successful implementation of water recycling projects requires project specific knowledge, so it provides a starting point for recycled water suppliers and potential users. It includes a wide breadth of information on the industries and technologies in each of the four energy sectors and attempts to capture their potential recycled water demands.

The challenge in identifying such opportunities and defining quantities of water demands in these industries is that, with the significant exception of the PHP sector, most of the industries covered are new or "immature" industries and technologies, and in many cases are not yet fully commercialized. As a result, the information provided herein is based on the best available information at this time. Chapter 3, the Industry Assessment section, includes a summary of the state of each industry, with information on expected trends for the near future in those industries, while acknowledging that these projections hinge on many factors outside of the scope of this study.

1.3 Organization

The remainder of this document is organized into the following sections:

- **Recycled Water and Industrial Water Reuse**. The objectives of this study are to connect the industries that compose the four energy sectors with the recycled water industry and serve as an introduction to recycled water treatment technologies for the audience of this study and of the Decision Support Tool. This section discusses those technologies and the typical quality of the water produced and how different technologies can produce water for specific uses. In particular, this section will summarize the typical requirements of industrial recycled water use and large-scale recycled water irrigation.

- **Industry Assessment**. This section covers the industries under each of the four energy sectors. It summarizes the technologies in those industries, identifies their water demands, describes water quality requirements for those demands, and assesses which demands have the greatest potential to be met by recycled water. It also identifies the water quality requirements each potential demand has, as criteria for selecting which level of treatment is required of the recycled water. Finally, industry-wide water demands are tallied to illustrate the potential quantity that could be met with recycled water.

- **Issues and Barriers**. Together with potential demand, other factors must be considered to determine the feasibility of using recycled water. This section discusses qualitative issues, including region-specific issues, that will either help drive or potentially impede the use of recycled water.

- **Decision Support Tool Overview**. The results of the study will be used as the basis for a Web-based Decision Support Tool for projects in the four energy sectors that could potentially use recycled water. The tool can be used by both sides of a potential project—the recycled water supplier looking for potential customers, or the energy/biofuels project lead investigating if recycled water is a feasible option. This section summarizes the purpose of the tool, describes its analytical capabilities, and demonstrates its format and user interface.

- **Conclusions and Recommendations**. This study is a starting point to bring together representatives of the recycled water industry and the various industries within the four energy sectors. This section describes some additional steps and recommendations that can be implemented to further the goal of expanding recycled water use in these emerging energy sectors.

1.4 Methodology

The methodology for this study included the following steps:

- **Literature review**. The project team began the process of compiling existing information regarding water use and requirements within each of the four energy sectors by searching for existing research, government reports, industry data, and other sources relevant to the scope of this project. Research and related work regarding water use in energy and biofuels is ongoing, so monitoring for new reports and papers continued throughout the project.

- **Interviews**. The project team then identified potential interview subjects in each of the four energy sectors to expand on information found in the literature and direct the project team to additional relevant information.

- **Compile Industry Data**. The potential for recycled water use in the four energy sectors depends on both the existing water demand in those industries and the industries' potential for growth. The project team compiled data from each industry in the four energy sectors to determine the existing extent of water demand in these industries as well as the potential for expansion, given rising energy and fuel demands. Data for this step came from two main sources: the federal government and industry-specific groups. Some industries covered by this study are well-established, mature technologies (e.g., fossil fuel–based power generation), so data for existing capacity are well documented, and projections are relatively less uncertain than for those industries with less developed and commercialized technologies. For those industries in which projections of future growth are more uncertain, the data compiled herein are based on the best available information and subject to revision.

- **Analysis**. The data compiled were used for the following analyses:

  1. **Quantify demands and potential supply**. The maximum potential demand for recycled water in the wide breadth of industries covered in this study was calculated based on water use factors (in units of volume of water per unit output) developed for specific water uses (e.g., cooling towers, boiler feed, and irrigation) in specific industries or technologies. Selection of water source will depend largely on site- and project-specific factors, so the project team also

estimated potential demand for specific regions where other factors will drive projects to select recycled water.

On the supply side, the project team compiled data on the existing wastewater and recycled water treatment facilities that could potentially supply projects in the four energy sectors and included them in the Decision Support Tool Overview.

2. **Define water quality requirements**. Recycled water quality must match the requirements of the intended user, so water quality requirements were developed for the industries and uses found under the four energy sectors with as much specificity as possible.

3. **Identify cost factors**. Ultimately, the largest influence on the selection of recycled water for a project will be cost. The project team qualitatively identified typical cost considerations for these projects and developed general cost guidelines for typical project components.

4. **Define factors that influence selection of recycled water**. In addition to the quantitative data defining water demands and requirements, there are many qualitative considerations that contribute to the selection of a water supply source. The project team analyzed potential factors that can contribute to either helping or hindering the use of recycled water for a given project. These factors include reliability, regulatory requirements, institutional agreements, and availability of water supplies, among others.

- **Report**. The results of all analyses described here have been summarized into this project report.

- **Develop Decision Support Tool**. To provide more guidance to users looking to expand their use of recycled water in the four energy sectors, the project team created a Decision Support Tool. This tool is a Web-based, interactive interface that incorporates geographic data so that the user can perform a screening-level analysis to determine whether recycled water is appropriate for each individual project.

Chapter 2

Recycled Water Production and Case Studies

In order to foster the process of introducing the recycled water industry to the industries in the four energy sectors, this section provides an overview of recycled water—how it is defined, the technologies used to produce it, and the typical water quality, given the treatment technology. An overview of each treatment technology is given with an emphasis on how the technologies can be applied to potential uses in the four energy sectors.

2.1 Recycled Water Definitions

Recycled water is generally defined as the reuse of treated wastewater for beneficial purposes, such as agricultural and landscape irrigation, industrial processes, toilet flushing, or replenishing groundwater basins. Recycled water is produced by passing treated wastewater effluent through one or more additional treatment steps beyond required wastewater treatment, resulting in a water supply with a quality high enough to be beneficially reused. Related terms such as "water reuse," "water reclamation," and "water recycling" can mean different things in different industries, but in the recycled water industry, they most often refer to reusing, reclaiming, or recycling municipal wastewater effluent.

To more precisely define typical recycled water, it is necessary to discuss the typical wastewater treatment steps that precede the production of recycled water. Wastewater is traditionally treated with a minimum of two steps:

1. **Primary treatment** typically includes removal of settleable solids by sedimentation.
2. **Secondary treatment** typically includes degradation (oxidation) of the dissolved organic material in wastewater through a combination of biological processes and sedimentation. Secondary treatment can also include physical separation via membranes.

Figure 2.1 shows a general flow schematic for a typical wastewater treatment plant with tertiary filtration.

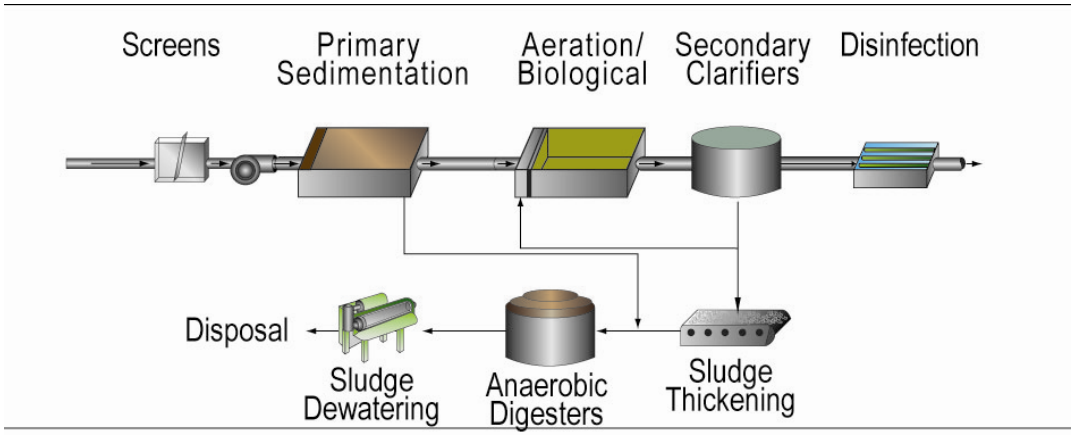

Figure 2.1. Typical wastewater treatment flow schematic.

Secondary treatment effluent ("secondary effluent") can be reused in applications that do not require high water quality and is typically permitted by regulatory agencies as long as public access to the areas of use is restricted. Applications include irrigation of agricultural crops not fit for human consumption, such as biomass feedstock crops. Secondary effluent can be preferable to other types of recycled water in some cases, such as growth media for algae to create biomass feedstocks. Algae can thrive in secondary effluent while improving its quality.

For uses requiring higher water quality, secondary effluent can be delivered to a reuse site and receive additional point-of-use treatment or conditioning to fit the water quality needs of that use, such as boiler feed or cooling tower make-up. One example of this is the Palo Verde Nuclear Generating Station near Phoenix, AZ. It receives secondary effluent that has been nitrified and disinfected (known as "Class B+ Reclaimed Water" in the state of Arizona), which is used for the power plant's cooling towers.

Most relevant to this study is the type of recycled water known as tertiary treated recycled water. Tertiary treated recycled water, or "tertiary effluent," is wastewater effluent that has been treated with one additional step beyond the process shown in Figure 2.1. The specific definitions of tertiary treatment and tertiary treated effluent can vary based on jurisdiction, although they are typically similar in practice. In most if not all cases, disinfected tertiary treated recycled water is allowed to be reused with no public restrictions regarding contact, although direct ingestion of this type of water is currently prohibited in all states. In jurisdictions that have recycled water regulations, tertiary effluent is the most commonly produced and available form of recycled water and the most likely source of recycled water for users in the four energy sectors.

2.2 Advantages of Recycled Water

Recycled water offers a few notable advantages over other water supplies. These advantages are discussed in more detail in Chapter 4, Issues and Barriers, but an overview is provided here.

- **Supply reliability**. Because recycled water originates from wastewater, its production is relatively steady throughout the year, independent of yearly climatic variations (e.g., drought). This feature is especially beneficial to industrial users who require full reliability of their water supplies. Irrigation users utilizing recycled water avoid reduced supplies during drought years, when irrigation demands rise. There

may be seasonal variations in flow (5% to 20%), depending upon how much seasonal groundwater, stormwater (in combined sewer systems), and rainfall based infiltration inflow is processed by the wastewater treatment plant. There will be a baseline of reliable supply in all years, however, even historically dry years. For this reason, recycled water is typically considered a drought-proof supply.

- **Lower cost**. Recycled water can have a price advantage over other water supplies. Recycled water utilities commonly structure rates to be less than potable water rates in the same service area. Some methods of structuring rates include setting them at a specified fraction of potable water rates (e.g., 80%) or setting rates to recover the operating costs of recycled water treatment. Some states and the federal government (through the State Revolving Fund loan program) provide financial incentives—via grants and low interest loans—for recycled water projects, reducing the direct capital cost to recycled water agencies, thereby allowing for lower rates. Two other considerations can limit the applicability of recycled water in these applications: (1) if the distance between a potential use site and the source wastewater is far enough, the cost of conveying flow to the site can overcome the potential cost savings of recycled water versus potable or other sources; or (2) if additional treatment is required at the use site to meet the water quality requirements of that user, when other sources of water do not require additional treatment, the potential capital and operations and maintenance (O&M) cost can outweigh the benefits of recycled water.

- **Reserves potable water supplies**. In areas with limited water resources, industrial and irrigation water demands can be seen as competitors with urban and residential water users for high-quality drinking water supplies. Reserving potable water for its highest beneficial use (typically considered human consumption) while providing recycled water for industrial and irrigation demands can ease the perception of competition and alleviate problems of limited water resources in a given area. This advantage can be significant if an agency with regulatory jurisdiction will not approve a project that puts a strain on existing potable water resources in an area.

Despite these advantages, there can be drawbacks to recycled water, depending on the alternative source of water. Chapter 4, Issues and Barriers, discusses these considerations in greater detail.

2.3.1 Tertiary Treatment

2.3.1 Treatment Technologies

State regulations can define the acceptable technologies for tertiary treatment, but in the absence of such regulations, industry practice has guided its selection. Available industry standard technologies for tertiary treatment include

- sand or granular media (depth) filtration
- cloth media (surface) filtration
- proprietary media filtration (e.g., technology such as Fuzzy Filter™)
- membrane filtration (e.g., membrane bioreactor, microfiltration [MF], and ultrafiltration [UF])

For a process to qualify as tertiary treatment, state regulations typically require a certain effluent limitation for solids removal, usually measured by turbidity or total suspended solids (TSS). All of the treatment technologies listed here are capable of satisfying these requirements, given suitable source wastewater quality. The most commonly implemented method of tertiary treatment is granular media filtration, which is a cost-effective method for reducing turbidity and removing additional solids.

Membrane filtration has the ability to treat wastewater effluent to a higher level than the other options, so membrane-treated recycled water has more potential uses. The tertiary effluent quality depends on the quality of the supply of wastewater effluent being treated; Table 2.1 explains the general capabilities of tertiary treatment systems utilizing the listed technologies. Figures 2.2 through 2.5 show some examples of these technologies in operation.

Table 2.1. Typical Tertiary Recycled Water Treatment Capabilities

Technology	Description
Media filtration, including	• removes solids (e.g., TSS) • can be enhanced with chemical addition to promote flocculation and additional solids removal • improves turbidity to regulatory limits • does not remove dissolved solids (e.g., TDS, salinity, ions) • cost effective
• sand • granular media • cloth media • compressible media	
Membrane filtration	• produces higher quality effluent than media filtration • removes more solids • increased capability to reduce turbidity • higher capital and O&M costs

Notes: O&M=operations and maintenance; TDS=total dissolved solids; TSS=total suspended solids

Figure 2.2. Continuous backwash granular media filtration.

Figure 2.3. Cloth media filtration.

Figure 2.4. Fuzzy Filter ™.

Figure 2.5. Skid-mounted membrane bioreactor.

2.3.2 Typical Water Quality

It is difficult to broadly define the water quality of recycled water; it depends directly on the quality of the source wastewater, which in turn depends on many specific features of the area where the wastewater is generated. The following factors contribute to the water quality of recycled water:

- **Drinking water source**. Some constituents found in drinking water are not removed or changed by either the drinking water or wastewater treatment processes. This aspect is particularly true of salinity, except where desalination or demineralization (e.g., reverse osmosis [RO]) is used for drinking water treatment, which is still rare in the United States.
- **Customer discharges into wastewater collection system**. Users discharging to a given wastewater collection system dictate the quality of that wastewater, so they influence the quality of the treated wastewater and recycled water produced by the treatment system. The most influential users discharge high flows of high strength or high concentration wastewater to the system and tend to be industrial users. However, residential users can influence quality as well; for instance, if large numbers of residences use water softeners, the total dissolved solids (TDS) of the wastewater tends to be elevated.
- **Infiltration/inflow**. If a given collection system has a significant number of degraded pipes, groundwater or stormwater can flow into them. In certain locations, those water sources can have elevated levels of constituents, such as salts or metals, which can pass through the wastewater and recycled water treatment processes.

There are particular constituents affected by these factors that are of greater concern for the potential recycled water demands involved in this study. These constituents include

- **Salinity** (i.e., TDS) is a concern to most users in all four energy sectors. Cooling towers are used by many industries in the PHP, BFPP, and BEPP sectors, and high salinity can limit the usefulness of recycled water by requiring higher blowdown (i.e., discharge to waste). For irrigation users, salinity can reduce plant productivity, contribute to salt build-up in soils without proper irrigation management, and even increase plant mortality.
- **Nutrients**. Recycled water can have elevated levels of nitrogen-based nutrients (ammonia, nitrate, and nitrite) if the wastewater is not treated by nitrification/denitrification. Ammonia is of particular concern to cooling tower users, as it can promote corrosion. Nutrients can also contribute to biogrowth in some facilities. On the other hand, nutrients can be beneficial when using recycled water for irrigation or as a growth medium.
- **Specific ions** (calcium, magnesium, sodium, chloride, carbonate, and bicarbonate, among others) can contribute to problems in cooling towers and irrigation applications for various reasons, depending on the ion.
- **Silica** can promote scaling in cooling towers, limiting the cooling efficiency.
- **Alkalinity and pH** can contribute to scaling in cooling towers by changes in solubility of select ions and can affect irrigation effectiveness depending on local soil conditions.

Actual concentrations vary widely depending on the specific wastewater treatment plant supplying the recycled water; Table 2.2 gives a range of the quality of typical recycled water offered to users. Table 2.3 lists water quality data from specific wastewater treatment plants as compiled for the Electric Power Research Institute (EPRI, 2008a). Because of variability, any project requires site-specific data and monitoring to determine whether the recycled water is acceptable as is or if additional treatment technologies or chemical conditioning steps are required.

Table 2.2. Typical Tertiary Recycled Water Quality for Selected Constituents

Constituent	Units	Typical Range
Salinity (TDS)	mg/L	400–1600
Ammonia	mg/L	1–75
Nitrate	mg/L	1–40
Calcium	mg/L	20–185
Magnesium	mg/L	20–150
Sodium	mg/L	150–500
Sulfate	mg/L	60–300
Phosphate	mg/L	1–50
Silica	mg/L	10–50
Alkalinity	mg/L as $CaCO_3$	100–250
pH	mg/L	7.0–8.0

Source: Adapted from Vidic, 2009.
Note: $CaCO_3$=calcium carbonate

Table 2.3. Example Water Quality from Sample of Treatment Plants

		Tertiary Treatment Plants								Advanced Treatment (RO)		
Constituent	**Unit**	**DDSD RWF**	**Santa Rosa**	**Lodi**	**Stockton**	**Current AWT Plant Tampa[1]**	**San Diego[2]**	**Grant Street WRF Melbourne, FL[3]**	**D.B. Lee WRF Melbourne, FL[3]**	**Aqua (III) Pilot San Diego[4]**	**Advanced Treatment Pilot Tampa[5]**	**Potable Reuse Pilot Denver[6]**
Na^+	mg/L	224	72.8	73	73	182	186	94	110	11.9	126	4.8
Mg^{2+}	mg/L	25	19.4				29.1			<3.0	0	0.1
K^+	mg/L	17	12.2			14.8	15.6					
Ca^{2+}	mg/L	53		29	29		65.3			<2.0		1
pH		7.3	7.5	7.0	7.0	7.19	7.06	7.4	7.44			
Alkalinity	mg/L	246		153	153		108					
Cl^-	mg/L	253	61.6	64	64	207	233	110	160	15	0	19
SO_4^{2-}	mg/L	219	34.4			207	216	49	50	0.1	0	1
SiO_2	mg/L	23		69	69							
NH_3-N	mg/L	24		2.0	2.0	0.1				0.8	0.03	5
NO_3^--N	mg/L	0.9	11.7			1.16	48.0	5.9	1.3	0.6	0	0.1
NO_2^-N	mg/L		0.17									
TKN	mg/L					1.2				0.9	0.34	5
Total N	mg/L	36										
Total P	mg/L	0.19	2.5			3.4	4.84			0.1	0	0.02
TDS	mg/L	930	428	377	377	972	890			42	461	18
TSS	mg/L			3.0	3.0	0.5	ND					
TOC	mg/L						9.1			0.27	1.88	0.2
BOD	mg/L						ND					
Turbidity	NTU	<2	<2	<2	<2	0.66	0.35			0.27	0.05	0.06
DO	mg/L					7.05						

		Tertiary Treatment Plants						Advanced Treatment (RO)				
Constituent	**Unit**	**DDSD RWF**	**Santa Rosa**	**Lodi**	**Stockton**	**Current AWT Plant Tampa[1]**	**San Diego[2]**	**Grant Street WRF Melbourne, FL[3]**	**D.B. Lee WRF Melbourne, FL[3]**	**Aqua (III) Pilot San Diego[4]**	**Advanced Treatment Pilot Tampa[5]**	**Potable Reuse Pilot Denver[6]**
Hardness	mg/L	233				339	281					
Aluminum	µg/L			0.035	0.035		99					
Arsenic	µg/L						0.55	2.2	<2.9	<0.5	0	ND
Barium	µg/L						34.5	5.9	15			
Boron	mg/L		0.370	0.2	0.2		0.343					
Cadmium	µg/L						ND	<0.2	<1.9	<0.2	0	ND
Chromium	µg/L						0.125	0.48	<0.66	<1	0	ND
Copper	µg/L		0.0034	0.003	0.003	1.9	10.3	5.8	2.7	11	0	9
Iron	mg/L		0.066	0.10	0.10	0.062	0.090	0.033	0.074	0.37	0.028	0.02
Lead	µg/L						ND	<0.33	<0.33	7	0	ND
Manganese	µg/L	0.082	0.032	0.027	0.027		61	6.7	17	8	0	ND
Mercury							ND			<0.2	0	ND
Nickel	µg/L						6.0			0.7	5	ND
Selenium	µg/L						0.74	<0.44	<0.44	<1	0	ND
Silver							ND			<1	0	ND
Zinc	µg/L		0.027	0.033	0.033		27.8	34	32	2.3	8	6

Notes: 1=City of Tampa Howard F. Current Advanced Wastewater Treatment Plant reclaimed water concentrations ending 3rd quarter 2011 (Tampa, 2011); 2=City of San Diego North City Reclamation Plant, Annual Monitoring Report 2010 (San Diego, 2010); 3=City of Melbourne Public Works & Utilities, Wastewater Department 2011 (Melbourne, 2011); 4=Aqua III pilot plant (Asano et al., 2007); 5= Hooker Point AWT pilot plant (Asano et al., 2007); 6=Denver's Potable Reuse Demonstration Project (Asano et al., 2007); AWT=advanced wastewater treatment; BOD=biological oxygen demand; Ca^{2+}=calcium cation; Cl^{-}=chloride ion; DDSD RWF=Delta Diablo Sanitation District Recycled Water Facility; DO=dissolved oxygen; K_{+}=potassium ion; Mg^{2}+=magnesium cation; N=nitrogen; Na+=sodium ion; ND=not detected at method limits; NH_3-N=ammonia nitrogen; NO_2—N=nitrite; NO_3—N=nitrate; NTU=nephelometric turbidity unit; P=phosphorus; RO=reverse osmosis; SiO_2=silicon dioxide; SO_4^{2-}=sulfate radical; TDS=total dissolved solids; TKN=total Kjeldahl nitrogen; TOC=total organic carbon; TSS=total suspended solids; WRF=water reclamation facility

2.4 Advanced Treatment

Treatment of recycled water beyond the tertiary level is generally termed "advanced treatment." This term is not strictly defined by regulations but more by industry practice. Advanced treatment involves the removal of targeted constituents to tailor the treated water to specific uses.

2.4.1 Nutrient Removal

Removal of nutrients, namely nitrogen and phosphorus, is most commonly required as a method to meet wastewater discharge requirements for secondary effluent. Nutrients can degrade receiving waters, but they can also be added to meet water quality requirements of recycled water users. In some recycled water applications, nutrients (ammonia) can be detrimental to operations; for example, ammonia removal is beneficial in cooling tower applications because it minimizes potential for corrosion of cooling tower fins and the degree of biocide needed for the cooling water to prevent biogrowth.

Nitrogen is removed from wastewater by various processes that promote nitrification (conversion of ammonia to nitrate) and denitrification (conversion of nitrate to nitrogen gas), but these treatment steps are typically part of the secondary treatment step, before tertiary treatment. Ammonia and nitrate can also be removed via RO; however, this method creates a concentrated brine stream high in nitrogen that requires disposal.

Phosphorus can be removed through treatment processes that promote biological uptake or by chemical precipitation and sedimentation. Phosphorus removal is typically not as much of a concern for most users in the four energy sectors.

2.4.2 Desalination and RO

Secondary and tertiary treatment processes are effective at removal of suspended solids and degradation of organic material through biological activity but are ineffective at dissolved constituents, such as salts. Desalination is the removal of dissolved constituents (e.g., TDS), also known as salinity. RO is currently the most common desalination technology used in the United States, although there are others available, such as electrodialysis reversal (EDR), various distillation technologies, and nanofiltration. Removal of dissolved constituents is required for some applications that require high purity water (e.g., boiler feed) or that concentrate the water they use through evaporation (e.g., cooling towers). RO treatment involves pressurizing feed water to overcome the osmotic pressure of the feed water solution, which allows nearly pure water to pass through semi-permeable, thin-film polyamide membranes while the dissolved ions remain in the feed water side.

RO treatment is the most common available technology to remove salts from water, although EDR is used widely for boiler feed purification, and nanofiltration is becoming more prevalent for applications that require reduced salinity but not to levels as low as those that utilized RO. The addition of RO or other desalination treatment can broaden the potential uses of recycled water to those requiring low salt content, such as high pressure boiler feed water. RO treatment has been successfully implemented in industrial applications of all types of water sources, from untreated surface water to recycled water. Design of RO systems can be tailored to the level of TDS removal necessary for a specific application.

RO treatment typically requires MF as a pretreatment step because constituents contained in secondary or tertiary effluent can contribute to fouling of RO membranes. Constituents of particular concern for fouling of RO membranes are

- **Total suspended solids (TSS)** can physically clog membranes and provide a substrate for biogrowth. Suspended solids also contain bacteria, the source of biogrowth.
- **Nutrients** encourage biogrowth and therefore biofouling.
- **Particulate matter**, especially those with angular surfaces, can damage membranes and accelerate the fouling process.

2.4.3 Advanced Oxidation Processes

Advanced oxidation processes (AOP) in general involve the use of oxidation to destroy organic constituents in water and wastewater. AOP is a relatively new process in wastewater and recycled water treatment, but implementation is increasing. It involves the addition of strong oxidants, such as ozone, peroxide, or ultraviolet (UV) radiation, to break down organic constituents that otherwise cannot be removed from the water. Recent concerns over low-concentration organic compounds—such as endocrine disrupting compounds, other pharmaceuticals, and personal care products, together known as constituents of emerging concern—have increased the likelihood that AOP will be a required treatment step in the future. Typically, there is no practical need to add an AOP step for users in the four energy sectors, barring future regulatory requirements.

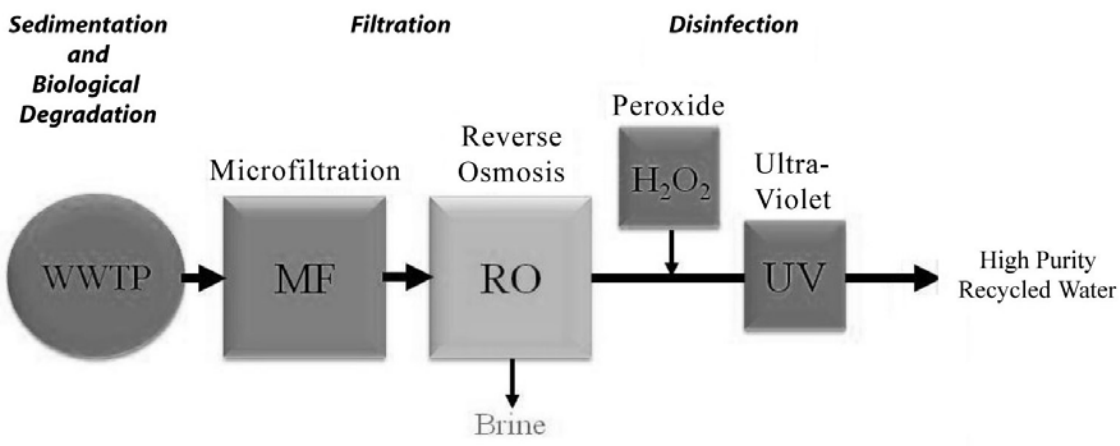

Figure 2.6. AOP schematic.

2.4.4 Implications for Users

These advanced treatment processes can be utilized along with tertiary treatment in different combinations to produce recycled water intended for specific uses. Advanced treatment can be added at the wastewater/recycled water treatment plant or at the point of use, such as a power plant or biofuels production facility. As discussed in Chapter 4, the first consideration when selecting a treatment configuration and processes is the recycled water quality requirements both for the user and as required by regulation. Other considerations, including

cost, responsibility/ownership of facilities, and operational agreements, will determine the location, capacity, and exact configuration of treatment options.

2.5 Disinfection Technologies

States with established recycled water regulations generally require a disinfection step that qualifies recycled water as tertiary treated as a measure to protect human health. Limited uses of recycled water can avoid the disinfection step; however, most uses covered in this study require disinfection. The selection of disinfection technology has less impact on the potential uses of the recycled water than the selection of filtration technology. Although the capital and operating cost of disinfection technology can influence the eventual cost paid by the user for recycled water, the quality of the recycled water, particularly in terms of constituents of interest to most industrial or irrigation users, typically does not depend on the disinfection technology selected. Indeed, regulations require disinfection to always be implemented to protect the health of workers and safeguard nearby populations, for example, from drifting vapor from cooling towers. Available disinfection technologies include

- chlorination (e.g., chlorine gas, hypochlorite, chloramines)
- UV radiation
- ozonation
- pasteurization
- peroxide (e.g., HiPOx process)

Chlorination is the most common disinfection process utilized in tertiary treatment. It offers the potential benefit of providing a residual in the distribution system that can suppress biogrowth when the water has reached the facility or use location. The other disinfection technologies are typically consumed rapidly during the disinfection process (ozonation, peroxide) or only effective in proximity to the disinfection equipment (UV and pasteurization), requiring additional biocontrol at the use site.

2.6 Recycled Water for Industrial Uses

Recycled water has been used to meet industrial water demands for decades, with some power plants reporting use of treated wastewater as far back as the 1960s (Veil, 2007). The most common use of recycled water in industrial applications, by measure of frequency and volume, is for cooling tower make-up water. Boiler feed is another common use; however, the quantity required for boiler feed is usually lower (about 10% of cooling water demand), and it requires a level of treatment higher than that of cooling tower make-up water.

2.6.1 Case Studies of Industrial Recycled Water Use

Currently, recycled water only makes up a small fraction of total water use by power plants and other industrial water users; however, several key examples illustrate that, under the right circumstances, recycled water is the best option as a water supply for these facilities. Lessons from these facilities can be applied more widely to other industrial facilities.

2.6.1.1 Case Study 1—Palo Verde Nuclear Generating Station

The Palo Verde Nuclear Generating Station is located about 50 miles west of Phoenix, AZ, and provides most of the electrical power demand for that city. Palo Verde is the only nuclear power facility in the world that is not located adjacent to a large body of surface water. Typically, nuclear power facilities have a large reserve of surface water available for cooling water because it is one essential method for preventing meltdown. Instead of relying on a surface water source, Palo Verde receives secondary treated wastewater from the five cities in the Phoenix area as its primary source of cooling water. The wastewater is further treated at the Palo Verde site to meet the water quality needs of its cooling towers.

The owners of Palo Verde recently negotiated a long-term water purchase agreement with the five cities who pump wastewater to Palo Verde to increase the amount of recycled water available from 105,000 to 185,000 AFY. The agreement also provided for a gradual increase in recycled water rates from the current rate of $53/AF to an ultimate rate of $300/AF.

Palo Verde is an important example of utilizing wastewater for its highest and most beneficial use. In particular, for regions with limited water resource availability, recycled water will increasingly become a more prevalent option for large water users such as power plants. Palo Verde can serve as an example for potential users in the biofuels and biomass industries as well as other power plants.

2.6.1.2 Case Study 2—West Basin Municipal Water District

West Basin Municipal Water District owns and operates the Edward C. Little Water Recycling Facility (ELWRF) in El Segundo, CA. ELWRF receives secondary treated wastewater from the Hyperion Wastewater Treatment Plant owned and operated by the city of Los Angeles. ELWRF is unique in that it produces five different types of recycled water (also known as “designer water”) to West Basin:

1. Tertiary effluent (as defined by California’s Title 22 standards) for both industrial and irrigation uses
2. Nitrified tertiary effluent, specifically to inhibit corrosion of metals in cooling towers
3. Softened RO water, which is secondary effluent filtered by MF, then RO, and disinfected prior to being injected into the ground for a seawater intrusion barrier
4. Pure RO water for low pressure boiler feed for the nearby Chevron refinery
5. Ultrapure RO water for high pressure boiler feed for the Chevron refinery

The users of these five types of water include the Chevron oil refinery, El Segundo Golf Course, and the injection pumps used to create a seawater intrusion barrier in the aquifer below the area.

Typically, distribution system capital costs are a huge driver in making a recycled water project feasible, so the ELWRF project is exceptional in that the five types of designer water each have their own distribution systems for delivery to their use locations. The location of the ELWRF is advantageous; it is immediately adjacent to the oil refinery, golf course, and seawater intrusion barriers, so the concentration of users results in reduced pipeline length.

2.6.1.3 Case Study 3—Delta Diablo Sanitation District and Calpine

Delta Diablo Sanitation District (DDSD) has operated its Recycled Water Facility (RWF) for more than 10 years, primarily providing tertiary treated recycled water to two power plants owned by the Calpine Corporation, the Los Medanos Energy Center (LMEC) and the Delta Energy Center (DEC). During the planning of these two power plants, water was identified as a potential hurdle due to cost and availability, and Calpine recognized the benefits of using recycled water as the supply source. Calpine came to DDSD, and the two entities agreed to develop the RWF in parallel with implementation of the two new power plants. Calpine paid for the construction of the tertiary treatment plant, which includes high-rate clarification (i.e., Actiflo), continuous backwash filters, and a chlorine contact basin as its main treatment processes.

Calpine and DDSD developed a water purchase agreement that ensured LMEC and DEC would be the priority users of recycled water but also allowed DDSD to utilize any additional flow and capacity to serve other uses. Calpine pays a recycled water rate that covers the O&M costs of producing the recycled water, which is lower than the rates it would have had to pay for other water sources.

This example demonstrates how recycled water suppliers can team with potential industrial users during planning stages of projects to identify and implement the use of recycled water as an alternative to other sources, whether in power generation or other large-scale industrial use. DDSD and Calpine partnered early in the process of planning a new project, which streamlined the process and set the stage for a successful, long-term project. To maximize the RWF treatment capacity, DDSD has since expanded use to multiple landscape irrigation customers and is continually looking to expand delivery to other users.

2.6.1.4 Case Study 4—Lodi and Northern California Power Agency

Lodi, CA, has provided tertiary treated effluent to the Northern California Power Agency's (NCPA) 49-MW, steam-injected, gas turbine power plant since 1993. Lodi leases land immediately adjacent to its White Slough Water Pollution Control Facility (WSWPCF) to the power plant and, as part of that lease agreement, delivers a minimum of 0.55 MGD of tertiary treated effluent to the plant for cooling water.

More recently, Lodi has worked with NCPA as the agency planned a new power plant to be located adjacent to the WSWPCF. The new 300-MW plant, dubbed the Lodi Energy Center, will use an annual average of 1380 AFY of tertiary treated effluent from the WSWPCF. As part of the planning process for the Lodi Energy Center, Lodi has guaranteed NCPA through a "will serve" letter that it will provide sufficient water supply to the power plant.

These two projects represent a common characteristic of existing, successful recycled water projects for industrial users, which was demonstrated by the previous case studies as well: the concentration of industrial users close to the recycled water source. The closer the user to the source of recycled water, the more economical the cost will be. Other factors tend to be more important for selection of a site for power generation; for example, the Lodi Energy Center project also happens to be located close to high-voltage transmission lines. When those factors are combined with proximity to a wastewater treatment plant, the possibility of a successful recycled water project grows.

2.6.1.5 Case Study 5—Santa Rosa and the Geysers

Santa Rosa, CA, has provided tertiary treated recycled water to Calpine's the Geysers geothermal power generation field since 1998. The project is unique in that it is, by far, the world's largest operating geothermal power generation field, and it utilizes the most recycled water (11 MGD and growing) of any geothermal project. The Geysers has been in operation for more than 40 years but began losing power generation capacity in the 1990s as the natural water supplies in the ground were extracted and evaporated away as part of the power generation process. Injection of recycled water allowed for renewed power generation capacity (Calpine, 2010).

Unlike the previous case studies, the Geysers is quite far from the source of recycled water (41 miles away). In this case, however, the economics of maintaining power generation capacity outweighed the conveyance capital and O&M costs associated with conveying the recycled water to the point of use. The Geysers is unique, but it represents an example of recycled water meeting a need where no other water source could work, as the power generation capacity of the project would have slowly decreased without a source of water to replenish the geothermal field.

2.7 Recycled Water for Agricultural Irrigation

As with industrial recycled water use, there is a long history of large-scale, agricultural irrigation using recycled water. For this study, the focus is on the potential for recycled water irrigation of biomass feedstock crops. Recycled water use for these types of crops has an advantage over others because the crops are not for human consumption, so contamination is of little or no concern. Nevertheless, there is a long history of using recycled water for agricultural irrigation of crops grown for human consumption, and such examples demonstrate the potential for using recycled water for this purpose.

The United States Department of Agriculture (USDA) and the WateReuse Research Foundation published a report, *Opportunities and Challenges in Agricultural Water Reuse* (2008), which included several case studies of successful use of recycled water for agricultural irrigation, including one from one of this study's participating agencies, Santa Rosa, CA. Those case studies are summarized here.

- **Santa Rosa**, a participating agency on this study, has used recycled wastewater for agricultural irrigation since the 1950s and implemented tertiary treatment in the 1990s. Recycled water is used to irrigate a variety of crops: pasture lands, legume and corn silage, hay, turf/sod, vegetables, and wine grapes. Located in the heart of wine country, Santa Rosa has partnered with wineries to ensure that the vineyards receive proper irrigation, even in drought years. In 1997, Gallo Wines shared the cost of a recycled water storage reservoir and conveyance system with Santa Rosa to expand recycled water use for its vineyards. As of 2009, Santa Rosa irrigates 3965 acres of pasture and fodder crops, 1506 acres of vineyards, and 237 acres of vegetables and other specialty crops (Santa Rosa, 2009).

- **Monterey Regional Water Pollution Control Agency (MRWPCA)**. One of the most extensive and groundbreaking projects related to agricultural irrigation with recycled water is the Salinas Valley Reclamation Project, in conjunction with the Castroville Seawater Intrusion Project. After years of overdraft of local groundwater

aquifers, the areas near the coast of Monterey Bay at the mouth of the Salinas Valley began experiencing seawater intrusion into the aquifers. Having exhausted most other available water supplies in the area for urban and agricultural use, the only option for local farmers was to turn to recycled water from MRWPCA. Starting in 1976, the project included years of studies (known as the Monterey Wastewater Reclamation Study for Agriculture, or MWRSA) to confirm that use of recycled water would not pose a threat to people eating the crops grown in the area. The MWRSA confirmed the safety of recycled water irrigation for these crops (Sheikh et al., 1990).

- **Recycled water irrigation in Florida**. Agricultural irrigation with treated wastewater has been utilized in Florida since 1966. Today, the state irrigates 13,914 acres of edible crops with recycled water, including its famed citrus fruits. In addition, farms in Florida irrigate 24,126 acres of nonedible agricultural crops with recycled water, including grazing land, timber, biomass, sod, seed, and hay. Florida keeps a comprehensive database of recycled water use called the Reuse Inventory Database and Annual Report. The latest version of the database shows that recycled water has been used to irrigate 13,115 acres of edible crops and 25,497 acres of nonedible crops (e.g., forage), with an annual average demand of 73.2 MGD (Florida Department of Environmental Protection, 2011).

Recycled water for irrigation of agricultural crops has proven to be safe. Now, the main concerns when selecting recycled water as the irrigation source have more to do with water quality and its effect on the type of crop to be irrigated. Water quality guidelines vary widely according to the specific crop and the constituent of concern; however, some general guidelines for constituents typically found in recycled water are shown in Table 2.4. Typically, recycled water quality falls in the range of the “slight to moderate restrictions” category shown in this table.

Table 2.4. Guidelines for Interpretation of Water Quality for Irrigation

Potential Irrigation Problem	Units	No Restrictions on Use	Slight to Moderate Restrictions	Severe Restrictions on Use
EC_w	dS/m	<0.7	0.7–3.0	>3.0
TDS	mg/L	<450	450–2000	>2000
SAR	unitless	and EC_w:		
0–3		<0.7	0.7–0.2	<0.2
3–6		<1.2	1.2–0.3	<0.3
6–12		<1.9	1.9–0.5	<0.5
12–20		<2.9	2.9–1.3	<1.3
20–40		<5.0	5.0–2.9	<2.9
Sodium[1, 2]				
Surface irrigation	SAR	<3	3–9	>9
Spray irrigation with foliage contact	mg/L	<70	>70	--
Chloride				
Surface irrigation	mg/L	<140	140–350	>350
Spray irrigation with foliage contact	mg/L	<100	>100	
Boron	mg/L	<0.7	0.7–3.0	>3.0
Nitrogen (Total N)[3]	mg/L	<5	5–30	>30
Bicarbonate (overhead sprinkling only)	mg/L	<90	90–500	>500
pH	unitless		normal range 6.5–8.4	
Residual chlorine (overhead sprinkling only)	mg/L	<1.0	1.0–5.0	>5.0

Notes: 1=Most tree crops and woody ornamentals are sensitive to sodium and chloride. Most annual crops are not as sensitive. 2=With overhead sprinkler irrigation and low humidity (<30%), sodium and chloride greater than 70 or 100 mg/L, respectively, have resulted in excessive leaf adsorption and crop damage to sensitive crops. 3=Total Nitrogen should include nitrate-nitrogen, ammonia-nitrogen, and organic nitrogen. Although forms of nitrogen in wastewater vary, the plant responds to the total nitrogen. dS/m= deciSiemens per meter; ECw=electrical conductivity of irrigation water; SAR=sodium adsorption ratio; TDS= total dissolved solids

Source: Adapted from University of California Committee of Consultants, 1974.

Chapter 3

Industry Assessment

The Industry Assessment is an overview of all technologies and industries covered within the four energy sectors of this study. Many within this wide range of industries are based around relatively new technologies that are still evolving. This chapter is an attempt to capture the current best knowledge of the state of these industries and present preliminary projections of growth based primarily on U.S. government data in order to anticipate growth and potential for water demands in these industries. The intent is to broadly describe these technologies and industries and identify the water demands of each as well as their potential water quality requirements.

3.1 Water Demand Terminology

Before delving into the industries and technologies of the four energy sectors, it is necessary to define terms related to water demands. To identify potential recycled water demands in the four energy sectors, the key information for a potential supplier of recycled water is a facility's required **water withdrawal**, or water withdrawal demand. This is the demand that would need to be met by the water supplier for the project, whether it delivers recycled water or water from another source, such as surface water or an aquifer.

At the facility, a portion of the water withdrawal demand is consumed by the process that uses the water. For example, a recirculating cooling tower evaporates a portion of the delivered water, which escapes to the atmosphere and is not recaptured. This portion of the delivered water that is lost is called **consumptive water demand**. The difference between the water withdrawal demand and the consumptive demand is typically discharged, either to a sanitary sewer system or a body of water. This remaining water could also be disposed of via zero liquid discharge (ZLD) facilities. For irrigation applications, the difference between withdrawal and consumptive demand is typically zero—applied water is either lost to the atmosphere via evapotranspiration, used to create plant tissue, or lost to the groundwater beneath the crops.

The distinction between water withdrawal and consumptive demand is essential because the key piece of information for water resource planning of a facility within the four energy sectors is the quantity of water that needs to be delivered to a facility or operation. A potential recycled water supplier needs to know a facility's water withdrawal demand in order to identify the treatment, conveyance, and storage requirements needed to meet that demand. A facility trying to identify its source of water for operations must also know and plan for the amount that needs to be delivered to its water connection point. Therefore, water withdrawal demand is the key data point for planning these facilities.

3.2 Power and Heat Production

The first of the four energy sectors is PHP. Of the four energy sectors, it is the most established in terms of pure size and the maturity of the technologies used. The PHP sector's range of industries and technologies includes traditional, fossil fuel–based power generation and renewable energy sources such as geothermal and CSP. This sector also includes the emerging technology of carbon capture and storage (CCS).

The different industries and technologies under the PHP sector generally all involve the concept of thermoelectric power generation; i.e., the technologies burn fuel to heat water and convert it to steam, which is then used to move an electric generator, producing power. The industry categories included for discussion here are

- Traditional thermoelectric power generation
  - ✓ coal
  - ✓ natural gas
  - ✓ nuclear
- Renewable thermoelectric power generation
  - ✓ geothermal
  - ✓ CSP
- Combined heat and power (CHP), also known as cogeneration
- CCS

3.2.1 Traditional Thermoelectric Power Generation

The industries included in traditional thermoelectric power generation are fossil fuel–based (i.e., coal and natural gas) power generation and nuclear power. The term "traditional" in this context refers to the fact that these fuel types have powered the vast majority of electricity generation in the United States for the last century. These will continue to be the largest power generation industries in the United States in the coming decades. They represent, by far, the largest potential demand in all four energy sectors that could be met with recycled water.

Coal power stations typically consist of a furnace, in which the coal fuel is burned to heat the boiler (also known as the steam generator), where water is heated to steam. The steam turns a turbine to generate electricity, then it is passed through a heat exchanger that heats up cooling tower make-up water, causing it to evaporate. The cooled steam, now condensed to water, is returned to the boiler to cycle through the process again. Coal power stations can operate at a wide range of steam temperatures and pressures, which affects the overall efficiency of the plant.

The latest technology that has been applied to coal for power generation is the integrated gasification combined cycled (IGCC) configuration. This type of power station gasifies the pulverized coal into synthesis gas, or syngas, which consists mostly of carbon monoxide and hydrogen with a slag waste product produced from impurities in the coal. Other gaseous impurities (including hydrogen sulfide and ammonia) are removed from the syngas, which is then burned like natural gas in a combustion turbine. IGCC plants can achieve higher overall efficiencies than traditional boiler power stations and have lower air pollutant emissions (e.g., sulfur dioxide and mercury) than traditional coal plants. IGCC plants can utilize any form of carbonaceous material, including biomass. Biomass gasification is discussed in Section 3.4.

Natural gas power stations typically operate with a combustion turbine to generate heat and steam and a steam turbine as the electrical generator, a combined cycle configuration similar to IGCC coal plants. Natural gas combined cycle (NGCC) plants require much less cooling water per unit output than other traditional thermoelectric power plants.

The U.S. Energy Information Administration (EIA) projects that coal- and nuclear-fueled power generation will increase, even as natural gas and renewable energy increases as a share of overall U.S. energy production. The opportunities for replacing current water supplies used in these industries with recycled water are potentially vast. Moreover, new power plants are expected to come on line in the coming decades to replace soon to be retired plants (U.S.EIA, 2011a). Natural gas power generation is expected to grow as a percentage of overall production in the next 15 years because of the continued expectation that the cost of natural gas will remain low, which suggests that opportunities for supplying these new natural gas–fired plants with recycled water will rise in the coming years.

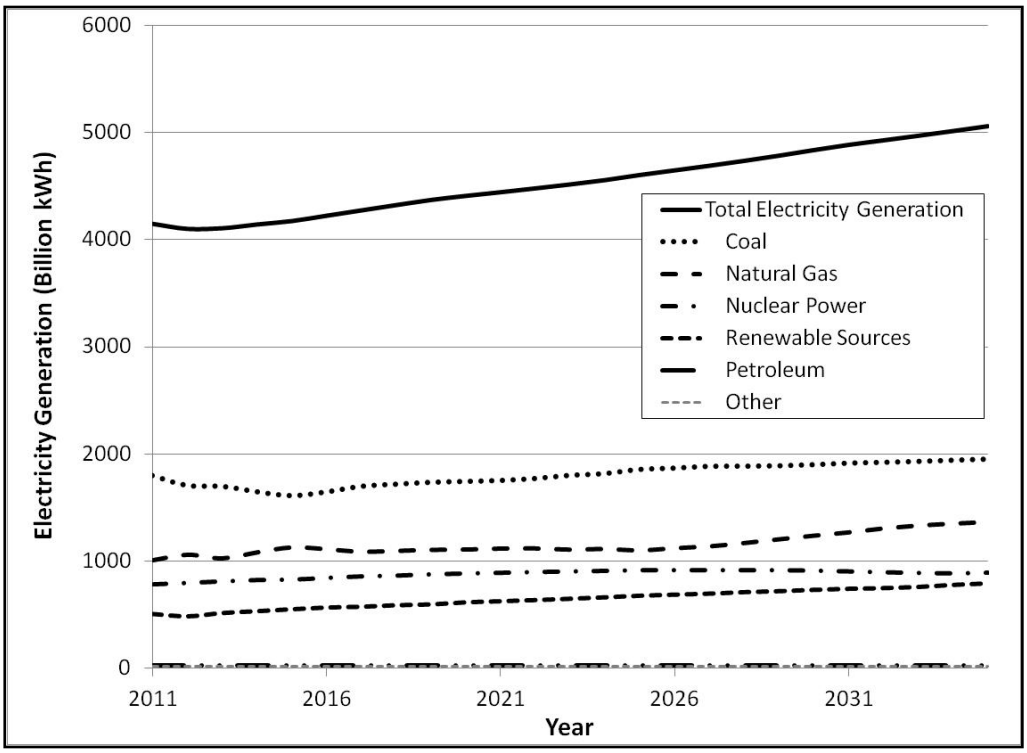

Figure 3.1. Previous and projected electrical power generation, 2011–2035.

Note: "Renewable Sources" includes hydroelectric, geothermal, biomass, wind, solar photovoltaic, CSP, and municipal solid waste (landfill gas).

Source: U.S. EIA, 2012

3.2.2 Renewable Thermoelectric Power Generation

Power generating plants that utilize renewable fuel and heat sources can also utilize recycled water. The two industry categories under the PHP sector include geothermal and CSP. Both technologies utilize the same thermoelectric power generation principles (i.e., Rankine cycle) as the traditional methods discussed previously, but they heat water to produce steam in very different ways.

3.2.2.1 Geothermal

Geothermal power generation utilizes naturally occurring heat near the surface of the Earth's crust, typically found in areas with high seismic/tectonic activity, such as the Western United States. There are a few different technologies that utilize hot geothermal fluids to produce electricity:

- **Dry steam** plants utilize hydrothermal fluids from the ground that are entirely in the form of steam rather than liquid water. The steam is directed to a turbine generator where electricity is generated, as it would in any other thermoelectric power plant. The Geysers power production facilities, utilizing dry steam resources in Sonoma and Lake counties in California, is situated in the largest geothermal steam field in the world. Dry steam reservoirs are exceedingly rare, and no additional dry steam reservoirs have been identified in the United States.
- **Flash steam.** Hydrothermal fluid above 360 °F (180 °C) can be utilized in flash steam plants. The fluid is typically highly pressurized and can be vaporized as it is brought to the surface, with the steam used to turn a turbine generator. Condensate from the process is reinjected into the ground.
- **Binary systems.** If the hydrothermal fluid has a lower temperature than necessary for flash steam systems (lower than 360 °F), it can be mixed with a secondary fluid that has a lower boiling point than the hydrothermal fluid, then vaporized. Moderate temperature groundwater is more widely available than high temperature or dry steam fields, so the potential for growth in the geothermal industry is highest with binary systems.
- **EGS** involves the injection of water into a geothermal resource in order to expand existing fractures or create new fractures, which improve water circulation below the surface and increase the electricity production potential of a given field. This method is controversial as some evidence has shown that it increases the seismic activity in the vicinity of a given geothermal field (Patel, 2009).

The largest existing geothermal installation in the United States is the Geysers, with approximately 1600 MW installed capacity, which represents about 50% of the total installed geothermal power generation capacity in the country. The Geysers is a clustered geothermal field owned by Calpine Corporation that already utilizes large volumes of recycled water to replenish the naturally occurring geothermal fluid that has been lost to evaporation as a result of evaporative cooling. The Geysers is a dry steam power plant, meaning the power plants that compose it use superheated steam directly from the ground to turn steam turbine generators. This type of plant is suitable for direct injection of recycled water, which allows the geothermal field to maintain electrical production output.

Production at the Geysers began to fall during the 1980s and 1990s because of cumulative losses of steam condensate extracted from the ground and lost to evaporative cooling. Injection of recycled water into the steam field reduced this trend. The Geysers initially received recycled water at flows of about 5 MGD but has increased steadily, with future projections showing up to 25 MGD by 2020 (Calpine, 2010). The keys to making this project cost effective were the proximity of recycled water to the steam field and power plant resources (within 40 miles) and the willingness of both public agencies and private power companies to invest capital. The public agencies (Lake County Sanitation District, other Lake

County communities, Santa Rosa, and its regional partners in Sonoma County) were willing to invest capital because it addressed a wastewater disposal issue for their communities, reducing discharges while beneficially reusing the water. The private entities (Unocal, PG&E, and Calpine) invested in the recycled water conveyance infrastructure to extend the useful lives of the Geysers' steam fields and power generation facilities beyond what would be possible without the additional water source, thus improving their return on investment.

Dry steam fields have the highest water demands, making them most compatible with recycled water use. Unfortunately, dry steam fields are also very rare, and the Geysers is the only dry steam power plant in operation in the United States.

Flash steam installations extract a highly pressurized, geothermally heated source of water from deep in the ground. The heated water is allowed to expand and vaporize, then the steam is used to turn a turbine generator. The steam is then condensed and reinjected to a cooled water aquifer in a closed loop system (Kagel, 2008). Flash steam installations, unlike other thermoelectric power generating technologies, can potentially operate without supplemental cooling tower make-up water; the steam or geothermal fluid from the geothermal field turns the steam generators and is then sent through condensers, with the collected, cooled water representing a large enough volume to typically meet cooling water make-up demand.

Reinjection of the cooled water needs to occur at a distance far enough away from the production well to not reduce the temperature of the geothermal reservoir, which could result in reduced performance of the power generating facilities. For geothermal reservoirs that are appropriate for utilizing flash or binary cycle configurations, the temperature of the reservoir is low enough that addition of cooled (or otherwise lower temperature) water too close to production wells can reduce the reservoir's overall temperature and limit energy production potential (Rybach, 2007). Injected recycled water would behave similarly to reinjected, cooled, geothermal fluids; if injected too close, they would reduce, not lengthen, the lifetime of the geothermal reservoir for power production. What makes dry steam reservoirs like the Geysers so valuable, in contrast, is that the temperature in the geothermal reservoir is high enough to immediately vaporize injected water, with little effect from the injected water temperature.

Experience with reinjection of supplemental water supplies, also known as augmentation injection programs, includes a few geothermal installations in addition to the Geysers. Geothermal fields like the Geysers and the Larderello field in Italy that are vapor-dominated, meaning the fluid is at a high enough temperature that most of that which is extracted is in vapor form, have a higher potential for augmentation injection. Other established geothermal installations that have implemented augmentation programs include the Dixie Valley facility in Nevada, which is liquid dominated, and Ngawha field in New Zealand. Liquid-dominated fields have a much smaller demand for supplementary water to maintain geothermal reservoir pressure than do vapor-dominated (Grant and Bixley, 2011). Augmentation injection is an opportunity for use of recycled water as the supplementary water supply; however, more detailed investigation on a site-by-site level is required to determine potential demands.

Geothermal power installations do need cooling towers to maximize thermal efficiency of their power production facilities, just like any other thermoelectric power plant. However, as mentioned previously, flash-type geothermal configurations can generally utilize condensed geothermal fluid without need for supplementary supply. Binary plants keep geothermal fluids in a closed loop configuration and therefore need a supplementary source of cooling

water or use air cooling technology. The quantity of water needed depends on the geothermal facility size (Mendrinos et al., 2006).

Projections for geothermal energy show many new sites in development. The vast majority of proposed sites are located in Nevada, with 65 sites at various stages of development. California (30), Utah (12), Idaho (11), Oregon (9), and Alaska (7) all have multiple projects in development as well (Jennejohn, 2011). Most of these opportunities for geothermal power generation (roughly 75%) are categorized as conventional hydrothermal (unproduced), meaning they are sites that have not been developed for geothermal power thus far, and most have hydrothermal fluid that requires use of binary geothermal systems because the fluid temperature is moderate. Therefore, these projects require a significant initial capital investment to get started, as opposed to sites that already have geothermal wells drilled and power production facilities constructed. Also, the majority of these sites are suitable only for binary-type geothermal plants (~65%).

For dry steam facilities like the Geysers, the main water demand is for direct injection into the ground to produce steam. For flash and binary systems, the main water demand is for cooling water, although flash steam plants can utilize the geothermal fluid for most of its make-up water. Binary plants require considerably more water from non-geothermal fluid sources for cooling tower make-up than dry or flash steam systems.

3.2.2.2 CSP

CSP is another well-established renewable energy technology that has great potential for expansion in the United States, in particular in the Desert Southwest. All CSP technologies use reflected sunlight to generate enough heat to produce steam, which is then used to generate electricity. This study does not cover photovoltaic (PV) solar arrays, which have negligible water demands. Application of CSP is limited by the fact that it requires direct insolation; that is, CSP facilities cannot produce power without direct sunlight. This limitation leads to facilities being located in desert areas, such as the Mojave Desert in California and the Desert Southwest (southern Nevada, Arizona, and New Mexico).

The category of CSP includes the following technologies:

- **Parabolic troughs** use long, trough-shaped mirrors to direct sunlight at a tube of heat transfer fluid (typically an oil), which heats steam to spin a turbine and generator (see Figure 3.2). The troughs track the sun in one axis over the course of the day to maximize efficiency.

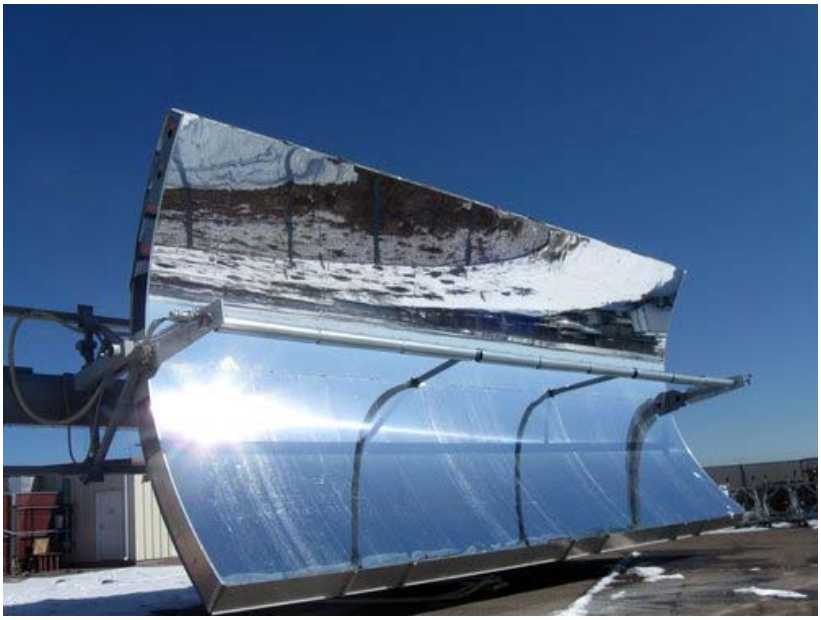

Figure 3.2. Parabolic trough mirror.
Source: NREL Photographic Information Exchange

Figure 3.3. Power Tower Solar Two in Barstow, CA.
Source: NREL Photographic Information Exchange

- **Power towers** consist of a large number of mirrors arrayed in a circular or semicircular field around a central tower. Each mirror directs the sun's rays toward the top of the tower where the light heats a heat-transfer fluid (usually molten salts), and from there the process of power production is very similar to parabolic troughs. Power towers are capable of operating at much higher temperatures than other forms

of CSP, so they can utilize dry cooling towers with less of a power penalty, even when situated in a hot, desert climate. The oldest installation of this technology is the Solar Two Power Tower near Barstow, CA, which was originally constructed in 1986 (see Figure 3.3).

- **Dish/Stirling** engine systems produce power differently than the two previous technologies. Each dish (mirror) has its own external combustion engine (i.e., Stirling cycle engine), as shown in Figure 3.4. The engines for each dish are air cooled, so they have a very small associated water demand, limited to that required for keeping mirrors clean.
- **Linear Fresnel system** has not been deployed on a large scale and is superficially similar to a parabolic trough, although it consists of many flat mirrors adjusted to reflect sunlight at a tube of heat-transfer fluid.

The major water demand for CSP is for cooling tower make-up. Because these systems are almost invariably located in remote, arid locations, water resources are scarce, so recirculating cooling towers are sometimes not feasible. Dry cooling towers pose a different problem because the typically hot climates of the facility locations reduce the cooling efficiency of the towers, an effect which is especially pronounced on the hottest days, when power demands are highest. Recycled water conveyed from the nearest municipality can address these problems.

Figure 3.4. Stirling dish CSP system.

Source: NREL Photographic Information Exchange

According to NREL, there are approximately 420 MW of CSP installations currently producing power in the United States, and an additional 4000 MW is scheduled to go online within 10 years. The currently installed facilities all utilize parabolic troughs, with the exception of a 5 MW power tower installation owned by eSolar near Lancaster, CA. The Solar One and Solar Two installations near Barstow, CA, also utilized power tower technology, but both have been decommissioned.

Several electric utility–scale CSP projects in California have recently been approved by the California Energy Commission (CEC) and will soon go into construction, including

- **Blythe Solar Power Project (Blythe, CA)**, originally licensed to have an ultimate installed capacity of 968 MW, will be the largest CSP installation in the United States when fully constructed and will utilize onsite groundwater for use as cooling tower make-up water. More information can be found at: http://www.blm.gov/ca/st/en/fo/palmsprings/Solar_Projects/Blythe_Solar_Power_Project.html (last accessed December 2011). However, the owner of the project, Solar Millennium, recently sold its rights to this and other projects to a solar PV project developer, Solarhybrid (*Renewable Energy World*, 2011). It is unclear how the project's plans for water supply will be affected by this change.
- **Beacon Solar Energy Project (Mojave, CA)** will have an ultimate installed capacity of 250 MW, utilizing parabolic trough technology. Water supplies will come from onsite groundwater resources, with estimated water use at 1600 AFY. More information can be found at: http://www.energy.ca.gov/sitingcases/beacon/index.html (last access December 2011).
- **Imperial Valley Solar (formerly SES Solar Two Project, near Ocotillo Wells, CA)** was originally licensed by the CEC to utilize the dish–Stirling engine technology (Sun Catcher), with an ultimate installed capacity of 750 MW. However, the project owner recently petitioned the CEC to terminate the license to resubmit the project with PV solar panels replacing the CSP technology. Originally, the project was planned to utilize recycled water from the nearby Seeley Wastewater Treatment Facility (SWWTF), and the project owner was to help finance improvements to the SWWTF to meet California's Title 22 tertiary effluent standards for recycled water use. It is unclear at this point whether the project will continue to need recycled water. More information can be found at: http://www.energy.ca.gov/sitingcases/solartwo/compliance/notices/2011-08-17_Order_Terminating_Commission_Decision_and_License_TN-61924.pdf (last accessed December 2011).
- **Rice Solar Energy Project (near Vidal Junction, CA)** will utilize central power tower CSP technology. The total installed capacity will be 150 MW, and it will utilize an air-cooled condenser (dry cooling tower) for cooling boiler feed. Water demands will be limited to mirror washing and replenishment of boiler feed, with an estimated demand of 180 AFY. Water supply will come from on-site groundwater wells. More information can be found at: http://www.energy.ca.gov/sitingcases/ricesolar/index.html (last accessed December 2011).

Other large capacity, pending CSP projects in California include Ivanpah Solar (power tower, 370 MW) in San Bernardino County; Genesis Solar (parabolic trough, 250 MW) in Riverside

County; Calico Solar Project (dish engine, 663.5 MW) in San Bernardino County; and Solar Millennium Palen (parabolic trough, 500 MW) in Riverside County. These facilities are all planning to use on-site or local groundwater for water supplies.

The decision to forgo recycled water in nearly all these recent cases reflects the impact of the additional costs of recycled water use. Recycled water sources are generally located many miles (10 or more) from the remote desert locations where these CSP installations are sited, so capital costs associated with a conveyance system (e.g., pipelines and pump stations) and additional treatment processes where tertiary level or higher recycled water is not yet available (as with the Imperial Valley Solar project) are high. Local groundwater use avoids these capital costs. O&M costs for local groundwater use are also more cost competitive than those for recycled water.

A more recent development, best illustrated by the Blythe and Imperial Valley Solar Projects, is that the cost of PV cells has dropped precipitously in the past year, while the cost of CSP has remained steady or grown. The shift to PV cells will greatly reduce the demand for water for these projects, as the primary water demand for PV projects is for washing the cells, which is orders of magnitude less than water demands for cooling. These examples illustrate how new, evolving industries can result in abrupt changes in direction. For recycled water suppliers, it is important to reach out to potential new users, but uncertainty of implementation must be taken into account. This topic will be discussed further in Chapter 4, Issues and Barriers.

3.2.3 Combined Heat and Power

CHP is the concept of using the heat that is normally wasted during the process of electric power generation for other processes at a plant or nearby facility, also referred to as cogeneration. Capturing that waste heat and using it for processes that would otherwise use other energy sources for heat results in an improved overall thermodynamic efficiency for a power generation facility. The opportunities for use of recycled water at CHP facilities are the same as those at other thermoelectric power generation facilities, with the additional demand of water used as a heat transfer fluid for other uses, such as building and facility heating and cooling. Cogeneration at large-scale thermoelectric power plants can help to preheat fuel and air used in the combustion process for better efficiency and to reduce incomplete combustion (WateReuse Research Foundation, in press).

CHP can be used in different configurations with great variation in scale. At one end of the spectrum, waste heat from energy generation is used for a specific, on-site heat demand. For example, wastewater treatment plants commonly employ anaerobic digestion to produce biogas, which is then burned to produce power. The anaerobic digestion process can be enhanced by heating the digesters with the waste heat, increasing the amount of biogas produced. Another typical CHP application is to use waste heat to preheat steam or boiler feed water prior to entering a boiler.

On the other end of the spectrum are so-called “district heating” (or district energy) systems, which employ hot water or steam distribution piping systems emanating from power generation facilities. The largest such system in the United States is owned by Consolidated Edison and serves most of Manhattan (the first implementation of district heating in the United States). District heating systems are most commonly implemented in densely developed locations, such as urban areas, college campuses, and hospitals. Based on a 2005 survey by the International District Energy Association (IDEA), there are district heating

systems at 330 college campuses, 85 urban utilities, and 123 hospitals in the United States (IDEA, 2005).

Water demands (both withdrawals and consumption) can vary widely depending on the exact design of CHP systems. Localized CHP systems, such as wastewater treatment plants with anaerobic digesters, often operate closed-loop systems that only require a small amount of blowdown and recycled condensate. On the other hand, district heating systems will sometimes deliver heated water or steam to customers, who are then responsible for disposing of condensate or reusing it for their own purposes (e.g., cooling water). These types of systems require a larger volume of make-up water for the district heating system, as the condensate is lost; however, these systems are not compatible with the most current uses of recycled water since there is potential for the heated water to come into full contact with users. Some district heating systems have condensate return distribution systems that improve the water use efficiency of the system. Because of the typically low pH of condensate in these systems, the condensate return piping tends to corrode over time, so many older systems (it is common for these systems to be more than 50 years old) have retired their condensate return pipelines as the piping has degraded. These systems with higher consumptive water demands may find the use of recycled water more appealing, if costs are lower than other sources (typically, municipal drinking water).

For these reasons, estimating potential water demands for district heating on a large scale is difficult. District heating is unlikely to be worthwhile for use with recycled water because of its lack of consumptive demand or, in cases where there is consumptive demand, the direct exposure of water to people.

3.2.4 Carbon Capture and Storage

CCS is the removal of carbon dioxide from exhaust (flue) gas created during fossil fuel–based power generation and the subsequent sequestration of that carbon dioxide in order to prevent it from entering the atmosphere. The purpose of CCS is to limit the levels of carbon dioxide in the atmosphere in order to mitigate the effect of elevated carbon dioxide levels as part of global climate change. CCS is a relatively new technology, and the term includes many different technologies that accomplish the goal of capturing and storing carbon dioxide.

Carbon capture can be categorized as follows:

- **Precombustion capture.** Here, the fossil fuel used for power generation is converted through gasification from a fossil fuel and water (steam) to syngas, which is a combination of hydrogen gas and carbon dioxide. The syngas has a higher concentration of carbon dioxide than the ambient air, which makes the removal process easier and reduces the power penalty for the overall plant. This process cannot be utilized at existing power plants that do not already have gasification technology installed unless the plant is retrofitted.
- **Postcombustion capture** is similar in concept to many other pollutant mitigation measures. Carbon dioxide is removed from flue gas after fossil fuels have been combusted during power generation. Any existing power plant could be retrofitted with postcombustion capture technologies; however, the addition of the capture equipment causes a significant power penalty to the next generation of that facility. The methods of postcombustion capture include

- ✓ Acid gas removal (i.e., amine gas treating) involves chemical absorption of carbon dioxide from flue gas into an amine solution, followed by stripping of the solution to release pure carbon dioxide. Research is ongoing to investigate the use of other chemical absorbents, such as ammonia (Herzog, 2009).
- ✓ Membrane separation. Research is ongoing to investigate the use of hollow-fiber membrane contactors to promote absorption of carbon dioxide into amino acid salt solution (Simons et al., 2010).
- ✓ Algae capture. Some research is being done to develop methods of bubbling flue gas through ponds or bioreactors being used to grow algae as a feedstock for biofuels.

Postcombustion capture represents the most readily available technology for retrofitting existing fossil fuel power plants; however, all the potential technologies result in a power penalty (i.e., parasitic loads) that reduces the overall power generation from the plant available to the grid. As a result, the amount of power generation needed to meet demands on the grid increases, with a corresponding increase in the water required for cooling. The power penalty to remove 90% of the carbon dioxide from the flue gas is approximately 25% (Herzog, 2009). Water is also used in the capture process for use in cooling the amine solution that has absorbed the carbon dioxide from the hot flue gases, although the water demand per unit of power plant output is not yet defined by industry practice.

- **Oxygen-enhanced combustion** involves injection of pure oxygen rather than air into the combustion process, which concentrates carbon dioxide in the flue gas. Combustion under these conditions produces flue gas mixture of nearly all carbon dioxide and water vapor. Water vapor can then be condensed, leaving nearly pure carbon dioxide, which can then be compressed. This type of configuration also requires a large parasitic load to power the oxygen generation equipment, so the result is an increase in cooling water demand.
- **Direct air capture**. Instead of capturing carbon dioxide emissions from power plant flue stacks, this concept involves capturing carbon dioxide from the air by deploying an array of decentralized capture equipment or by fixing carbon as part of biomass (e.g., trees) grown specifically for the purpose of sequestering carbon. Research is ongoing on the feasibility of these technologies, and some start-up companies have formed for the purpose of commercializing air capture equipment, for example Kilamanjaro Energy, but the feasibility of air capture as compared to other capture technologies has been questioned because of its much higher cost per ton of carbon captured (Ranjan and Herzog, 2010).

Methods of carbon sequestration are numerous and can be largely grouped into (1) biological processes, (2) physical processes, and (3) chemical processes.

- **Biological (biomass) sequestration** involves the incorporation of atmospheric carbon dioxide into plant tissue (biomass). Methods include
  - ✓ Creating new peat bogs, which consist of very slowly degrading dead plant material (e.g., mosses)
  - ✓ Planting and maintaining new tracts of forest (trees), but the trees must not be burned, allowed to rot, or removed, unless they are to be used for a purpose that permanently sequesters the biomass (e.g., durable goods, burial; NETL, 2010)

- ✓ Switching to no-till agricultural practices, which retard the process of degradation of agricultural residues (NETL, 2010)
- ✓ Enhancing biogrowth (algae and phytoplankton) in the ocean via artificial (iron) fertilization. As the biomass dies off, it is deposited to the ocean floor and sequestered (Buesseler et al., 2004).

- **Physical sequestration** involves physically excluding biomass or other forms of carbon sinks from the atmosphere. Methods include
  - ✓ Biochar, a byproduct of pyrolysis of biomass (i.e., coal converted to methane), is charcoal that is specifically used for sequestration, typically by adding to soil (Lehman et al., 2006).
  - ✓ Burial of trees or other biomass to prevent or slow the degradation of biomass
  - ✓ Geological storage, which is injecting supercritical (high pressure, high temperature) carbon dioxide into the ground, usually in former oil or gas formations (Lackner et al., 1995; Herzog, 2009)

- **Chemical sequestration** involves a reaction of carbon dioxide with metal oxides, including calcium and magnesium, to form calcium carbonate and magnesium carbonate. These processes are a natural form of mineralization that, under normal (i.e., low) temperatures, occur over geologic time frames. Speeding up the reactions requires additional energy input, which results in higher costs and water use for cooling in power generation (Keleman and Matter, 2008).

All these potential methods to both capture and sequester carbon dioxide require a significant additional cost on top of the current costs of producing fossil fuel power generation. In addition, all are in various stages of research and development, so their capital and operating costs are high now relative to their potential, commercialized costs in the future. As a result, the implementation of CCS technologies will be highly sensitive to future regulations and incentives. With no system in place, such as a carbon tax or emissions limit as part of a cap and trade system, these technologies will not be widely implemented because of their lack of cost competitiveness. As a result, many of these options, although theoretically feasible, have only been considered on the conceptual or initial research level (e.g., ocean fertilization or biomass burial).

Despite these caveats, there are some systems in place that are helping to drive development of these technologies, including

- **WCI** is a partnership of six U.S. states (California, Montana, New Mexico, Oregon, Utah, and Washington) and four Canadian provinces (British Columbia, Manitoba, Ontario, and Quebec) that have agreed to develop a collaborative cap and trade system. Six other U.S. states, one Canadian province, and six Mexican states have joined as observers to the development. California has since moved forward with its cap and trade system for power plant emissions, and collaborates with the Canadian provinces of British Columbia, Ontario, Quebec, and Manitoba to "develop and harmonize their emissions trading policies" (WCI, 2013).

- **RGGI** is a partnership of 10 northeastern U.S. states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont) and four observers (Pennsylvania and the Canadian provinces of

Quebec, New Brunswick, and Ontario). RGGI already implemented a cap and trade system exclusively for power plants in 2008. Its goal is to develop and maintain a carbon emission reporting system, implement a system of auctioning carbon dioxide emission allowances, monitor other carbon dioxide auction and trading systems, and provide technical assistance to partner state agencies.

- **California Global Warming Solutions Act (Assembly Bill 32).** California's Air Resources Board has been developing a system to limit carbon dioxide emissions, which is currently proposed to be a cap and trade system. Litigation has put development of the system on hold.

In addition to these initiatives, the U.S. Department of Energy (DOE) has provided grants and loan guarantees for the development of carbon capture and sequestration technologies.

The longest operating, full scale, CCS power plant is the Weyburn-Midale Carbon Dioxide Project. Carbon dioxide produced during syngas production (gasification) at the Dakota Gasification Company in Beulah, ND, is pumped to the Weyburn oil fields in Saskatchewan just over the U.S.–Canada border via a 205-mile pipeline and used to enhance oil extraction from the site. Carbon dioxide is removed as part of the syngas production process. The project has been in operation since 2000 and has sequestered more than 17 million metric tons of carbon dioxide. Many other plants are currently in development in the United States, including Skyonic, which has implemented a demonstration facility for CCS at a cement plant near San Antonio, TX. The technology uses a process of mineralization to produce baking soda (bicarbonate) from carbon dioxide released by the plant. The FutureGen 2.0 project is being partially funded by the DOE to implement a 200 MW oxy-combustion coal power plant in Meredosia, IL. The nearly pure carbon dioxide flue gas will be captured and stored in a geologic formation in nearby Morgan County, IL. The Southeastern Regional Carbon Sequestration Partnership has two ongoing, large-volume, carbon dioxide injection test sites, called the Early Test and the Anthropogenic Test. The Anthropogenic Test is a full scale carbon dioxide capture from the Alabama Power Company's coal-fired Plant Barry near Mobile, AL, with injection at the Citronelle Oil Field. Water use related specifically to carbon capture and storage typically involves the following:

- **Parasitic load.** The CCS technologies require significant additional power loads that reduce the overall power generation available for sale from a power plant, which results in overall larger power generation requirements to meet existing demands. This increase in power generation causes a subsequent, proportional increase in cooling and boiler feed water demand and depends on the fuel type and power generation technology.
- **Process water.** The available capture technologies utilize water for creating amine solution as part of the acid gas scrubbing process. The volume associated with this demand is orders of magnitude lower than the demand for cooling water because of the parasitic load.

3.2.5 Potential Water Demands

These industries and technologies differ by the type of fuel used to produce power and share many of the same water demands. Water demands that are potentially compatible with recycled water identified for the PHP include

- Cooling tower make-up water

- Boiler feed
- Air quality control process water
- Greenhouse gas scrubbing process water (CCS)
- CHP process water
- Wash down and other on-site uses

By far, the largest potential water demand is for cooling tower make-up. Boiler feed is generally the second largest water demand by volume, although its demand is typically 10% or less of the demand for cooling water. Boiler feed systems are generally closed systems, with only minimal consumptive demands due to periodic blowdown to maintain water quality. Coal-fueled power plants are the exception, where the water demand for air quality control measures (e.g., sulfur scrubbing) and ash handling can be greater than boiler feed requirements (NETL, 2005).

Demand for cooling tower make-up depends on the type of cooling tower technology. There are four main types of cooling towers:

- **Once-through cooling.** This type of cooling tower withdraws large amounts of water, typically from an adjacent, large body of surface water (lake, reservoir, river, or ocean), and passes it through a power plant to cool down the steam before discharging it back into the same body of water. It does not match well with recycled water because the required withdrawals for a typical power plant utilizing this technology are far larger than the production of most recycled water treatment plants. Once-through cooling is not likely to be implemented at new plants, as it has high environmental impacts (e.g., causes entrainment and uptake of aquatic species and elevates the temperature of the source water body). The U.S. EPA has proposed a new rule under Section 316(b) of the Clean Water Act to limit the number of deaths of fish or other organisms as a result of water intakes for power plants (U.S. EPA, 2011). If implemented, this proposed rule will likely result in retrofits of existing cooling systems to wet recirculating facilities. Once-through cooling is also beginning to be phased out in California by order of the State Water Resources Control Board, which may presage restrictions in other states.
- **Recirculating ("wet") cooling towers.** This technology is well matched to recycled water use. It involves cycling make-up water through the cooling tower to cool steam. Make-up water is passed through the cooling tower, absorbing heat from the steam and causing a portion of the make-up water to evaporate. A small quantity of the cooling tower water is also lost through drift of water droplets leaving the cooling tower. The consumptive demand of the system is the amount lost to evaporation and drift by the wind.
- **Air ("dry") cooling towers.** This technology uses forced air (e.g., fans) as the cooling method to exchange heat by convection. No water is required for the cooling tower, eliminating roughly 90% of a power plant's water demand. For this reason, existing air-cooled power plants would not find recycled water use as beneficial as those using evaporative cooling towers. Many newer power plants have been required by regulators to use dry cooling towers because they are located in areas with scarce water resources. A disadvantage of air cooling is that

there is a penalty to overall plant output because some output is used to power the fans and cooling efficiency is reduced if there is not a large differential in temperature between the heated power plant air and the ambient air. For new power plants facing the potential requirement of air cooling, the availability of recycled water in areas with otherwise scarce water resources would allow for improved plant performance.

The major disadvantages of dry cooling towers are the significantly higher cost versus that of recirculating wet cooling towers and greater land area required for installation. The capital cost of dry cooling towers depends largely on the design of the system, which in turn depends on the site-specific conditions, particularly climate. However, the cost is generally three to five times the capital cost of a recirculating cooling tower given the same site, so the selection of dry cooling towers is almost always driven by lack of water resources, environmental concerns, or a desire to limit the time period required for licensing the plant (EPRI, 2008b; Maulbetsch, 2002).

- **Hybrid cooling towers.** As the name suggests, hybrid cooling towers utilize a combination of wet and dry cooling techniques. Recycled water can be used for the portion of the system using water for evaporative cooling, as with wet cooling towers. Hybrid cooling has not been applied as widely as dry or recirculating cooling towers but is gaining popularity. Recent work has examined the impact of hybrid cooling towers on the efficiency of CSP power plants (Wagner and Kutscher, 2010). Implementing hybrid cooling systems would reduce the need for water year round, as the air-cooled condensers would be the primary cooling method during winter and portions of spring and fall, whereas the wet recirculating cooling towers would be used only when the air temperature is hot enough to reduce the overall power plant efficiency. This scenario introduces a challenge similar to irrigation water demands in that the water demand is concentrated during the summer months, while wastewater effluent is produced year round.

3.2.6 Treatment and Conditioning Practices

Regardless of the water source, thermoelectric power plants typically provide some type of additional treatment or water conditioning at the power plant site. Some of these steps would still be required beyond the tertiary treatment step at the recycled water plant, if recycled water were to be used. These steps can include:

1. Biocide. In order to prevent biogrowth on the cooling tower surface, biocides or hypochlorite are added. High nutrient levels exist in some recycled water, so biological growth can increase with recycled water use, and higher dosing of biocides may be required.

2. Surfactants are added to prevent attachment of biofilms to the cooling fin surfaces.
3. Sedimentation/clarification. Flocculants (e.g., ferric sulfate) and polymers can be added to make-up water and passed through a sedimentation tank to remove phosphates, magnesium, and silica.
4. pH adjustment. Acid can be added to lower pH and prevent scaling due to mineral content in the make-up water.

5. Scale inhibitors or dispersants can be added to prevent scaling.
6. Membrane filtration. Some plants have implemented RO membrane filtration to remove dissolved solids (salinity, minerals), particularly if the water is to be used for boiler feed. Membrane filtration can reduce or eliminate the need to provide other forms of conditioning as described previously.

Plants may also choose to retrofit their facilities to be more compatible with the chemistry of recycled water, for example, by switching from stainless steel and copper–containing alloys to titanium. Chlorides in high concentrations in recycled water can contribute to corrosion of ferrous metals and copper alloys.

3.2.7 Water Demand Quantities

Water demands for the types of energy production within the PHP energy sector are varied, with the primary water demand by volume being for cooling water. Thermoelectric power plants, whether fossil fuel-based or renewable fuel–based, use similar cooling water technologies, although the quantity of water supply required varies for each. Boiler feed is the next most significant demand and is also very similar for each type of energy production, but the amount is a few orders of magnitude lower than demands for cooling water. Table 3.1 lists the water demands for each use in the PHP sector.

Table 3.1. Cooling and Process Water Demands for Various Power Generation Technologies

Fuel/Power Station Type	Withdrawal Demand (gal/MWh)			Consumptive Demand (gal/MWh)		
	Median	Min	Max	Median	Min	Max
Cooling Water—Wet Recirculating Cooling Towers						
Coal, traditional steam	1005	500	1200	687	480	1100
Coal, subcritical steam	531	463	678	471	394	664
Coal, supercritical Steam	609	582	669	493	458	594
Coal, IGCC	390	358	605	372	318	439
Natural gas, combined cycle	253	150	283	198	130	300
Natural gas, traditional steam	1203	950	1460	826	662	1170
Nuclear	1101	800	2600	672	581	845
Biomass, traditional steam	878	500	1460	553	480	965
Geothermal, dry steam[1]	2000	--	--	--	1700	5147
Geothermal, flash [2]	10	5	19	10	5	19
Geothermal, binary	--	--	--	3600	1700	3963
Geothermal, EGS				4784	2885	5147
CSP, trough	--	--	--	865	725	1057
CSP, linear Fresnel	--	--	--	1000	1000	1000
CSP, tower	--	--	--	786	740	860
CSP, dish/Stirling engine[3]	--	--	--	0	0	0
Process Water						
Coal, traditional	--	30	100	--	30	100
Coal, IGCC[3]	--	130	140	--	130	140

Fuel/Power Station Type	Withdrawal Demand (gal/MWh)			Consumptive Demand (gal/MWh)		
	Median	Min	Max	Median	Min	Max
Natural gas, combined cycle	--	7	10	--	7	10
Nuclear	--	--	30	--	--	30
Geothermal, EGS[5]				900	400	1800
CSP, trough[6]	--	8	20	--	8	20
CSP, linear fresnel[6]	--	8	20	--	8	20
CSP, tower[6]	--	8	20	--	8	20
CSP, dish/Stirling engine[6]	--	8	20	--	8	20

Notes: 1=The water withdrawal estimate includes consumptive demands from both cooling water and direct injection to geothermal reservoirs, based on data from Calpine at the Geysers geothermal facility. The Geysers facility represents approximately 90% of the geothermal power production capacity within the United States. 2=Flash geothermal installations typically use geothermal fluids for cooling water make-up, so withdrawal demands for other sources of water are low. 3=Dish/Stirling engine solar technologies do not require cooling water. 3=Includes gasification process water (130 gallons/MWh); 4=EGS systems require water to be injected into the ground as part of the steam field development process. 5=All concentrating solar technologies use generally the same amount of water to wash mirrors at facilities. CSP=concentrating solar power; EGS=enhanced geothermal system; IGCC=integrated gasification combined cycle

Sources: Macknick et al., 2011; DOE, 2007

Dry cooling towers use the ambient air temperature to cool boiler water using a heat exchanger. Dry cooling towers do not have a consumptive water demand but suffer from reduced power production efficiency because they require motorized fans to force air through the towers. Dry cooling towers are becoming more prevalent in newly commissioned power plants, especially in areas with limited water resources, such as concentrating solar facilities located in the desert. Using wet cooling is generally preferred because it does not require as much parasitic power load, so if the economics of conveying it to a site are right, recycled water can prove advantageous to new facilities. However, it largely depends on site-specific conditions, such as the proximity of the nearest wastewater treatment plant, terrain from the wastewater plant to the power plant, and the wastewater flows available.

3.2.8 Water Quality Requirements

Water quality requirements for wet cooling towers are nearly the same for any power production application. The EPRI has produced guidelines for wet cooling tower technologies, which are presented in Table 3.2. Recommendations for boiler feed of varying pressures are shown in Table 3.3.

In addition to the guidelines listed in the table, air quality regulations may hinder the use of recycled water in cooling towers. Particulate matter less than 10 microns in diameter (PM10) emissions from cooling towers are estimated using the TDS concentration in the cooling tower as a proxy, based on the methods outlined in the U.S. EPA document, *Compilation of Air Pollutant Emission Factors*, also known as AP-42. Section 13.4 of the document describes the methods for determining the specific emissions factors used to calculate the correlation between TDS concentration in the cooling towers. The emission factors depend on the design and cooling tower equipment used at a specific site. As a result, TDS concentration limits in the cooling tower water vary from site to site but can be as low as 3500 mg/L, which can limit the cycles of concentration within the cooling tower to well below those based on

the concentrations listed in Table 3.2. Lower cycles of concentration mean higher water demand to meet cooling requirements as well as higher chemical conditioning costs.

Table 3.2. Wet Cooling Tower Water Quality Guidance

Constituent	Units	Former EPRI Standards (1982)	Current EPRI Standards (1998)	Refinery Cooling Systems (1993)
Ca	mg/LCaCO3	900 (max)	(see note 6)	1500 (max)
Ca x SO4	(mg/L)2		500,0005	(see note 9)
Mg x SiO2	mg/LCaCO3 x mg/LSiO2	35,0002 75,0003	35,0005	--
M alkalinity1	mg/LCaCO3	30–502 200–2503	(see note 6)	--
SO4	mg/L	--	(see note 6)	5000 (max)
SiO2	mg/L	150	1505	300 (max)
PO4	mg/L	<5 4	(see note 6)	50 (max)
Fe (total)	mg/L	--	<0.55	10 (max)
Mn	mg/L	--	<0.5	1
Cu	mg/L	--	<0.1	0.5
Al	mg/L	--	<1	1
S	mg/L	--	5	10
NH3	mg/L	--	<2 10	40 (max)
pH		6.8–7.22 7.8–8.43	(see note 6)	7-9
TDS	mg/L		70,000	--
TSS	mg/L		<100[7] <300[8]	200
BOD				200 (max)
COD				200 (max)
Langelier SI				<0
Rysnar SI			>6	
Puckorious SI			>6	

Notes: 1=M alkalinity=HCO_3 + CO_3, expressed as mg/l $CaCO_3$; 2=without scale inhibitor; 3=with scale inhibitor; 4=no recommendation given because of insufficient data; 5=Conservative value—reference is made to EPRI's SEQUIL RS for predicting case specific limits. SEQUIL RS takes into account parameters such as ionic associations, ionic strength (measure of background salt and ionic charge), pH, and temperature to predict the solubility of certain salts. 6=No value given—reference is made to EPRI's SEQUIL RS for predicting case specific limits. 7=<100 mg/l TSS with film fill; 8=<300 mg/l TSS with open fill; 9=No inference was made by the authors to the product of the Ca and SO_4 maximum operating values to be used to set a Ca x SO_4 limit (reference Kunz and EPRI values). 10=<2 mg/l NH_3 applies when copper bearing alloys are present in the cooling system. This does not apply to 70-30 or 90-10 copper nickel. Al=aluminum; BOD=biological oxygen demand; COD=chemical oxygen demand; Ca=calcium; Cu=copper; EPRI=Electric Power Research Institute; Fe=iron; M alkalinity=total alkalinity; Mg=magnesium; Mn=manganese; NH_3=ammonia; PO_4=phosphate; S=sulfur; SI=saturation index; SiO_2=silicon dioxide; SO_4=sulfate; TDS=total dissolved solids; TSS=total suspended solids

Table 3.3. Water Quality Requirements for Boiler Feed Systems

Parameters	Unit	Boiler Feed Water, bar			
		0–10	10–12	48–103	103–344
Silica (SiO_2)	mg/L	30	10	0.1	0.01
Aluminum (Al)	mg/L	5	0.1	0.01	0.01
Iron (Fe)	mg/L	1	0.3	0.05	0.01
Manganese (Mn)	mg/L	0.3	0.1	0.01	--
Copper (Cu)	mg/L	0.5	0.05	0.05	0.01
Calcium (Ca)	mg/L	--	0	0	--[2]
Magnesium (Mg)	mg/L	--	0	0	--[2]
Ammonia (NH_3)	mg/L	0.1	0.1	0.1	0.7
Bicarbonate (HCO_3^-)	mg/L	170	120	50	--[2]
TDS	mg/L	700	500	200	0.5
TSS	mg/L	10	5	0	0
Hardness	mg/L as $CaCO_3$	20	1.0	0.1	0.07
Alkalinity	mg/L as $CaCO_3$	140	100	40	0
pH	unitless	8–10	8–10	8.2–9.2	8.2–9.2
COD	mg/L	5	5	0.5	0
Dissolved oxygen	mg/L	<0.03	<0.03	<0.03	<0.005
Temperature	°C	49	49	49	49
Turbidity	NTU	10	5	0.5	0.05

Notes: 1= California SWRCB, 1963; U.S. EPA, 1973. 2=determined by treatment of other constituents; 3=This table is a general guideline. Specific water quality requirements may vary with each application, process, or technology.

Other technical and cost considerations for the PHP sector include the need for higher levels of water treatment for boiler feed or process water, on-site water storage to meet peak demand periods, and conveyance infrastructure to get recycled water to the use site.

3.2.9 Regional Considerations

Geographically, the parts of the United States with limited freshwater availability will have the greatest need for an alternative water source, such as recycled water, to meet water demands. Electrical generating capacity is constantly being expanded in growing areas to meet new demands, so there is a growing demand for water wherever these new plants are being built. In the arid West, there have been examples of new plants examining the use of recycled water but selecting air-cooled condensers (dry cooling) instead for a combination of economic and availability issues.

Current examples are the recent approval by the CEC of large-scale CSP facilities in the desert areas of Southern California, some of which will use recycled water for cooling. The Beacon Solar Project was recently licensed by the CEC and will use recycled water for its wet cooling tower system. Other recently CEC-licensed facilities, including the Blythe Solar

Power Project, which would have been the largest of its kind in the world, have not found it advantageous to use recycled water and were licensed to use dry cooling instead. However, now that that project is on hold and may switch technology from CSP to solar PV, its water demands are likely to be drastically lower than those proposed during the licensing process.

Even areas outside of the arid West have found use for recycled water at power generation plants. An example is the Mankato Energy Center in Mankato, MN, owned by Calpine. The plant has a 6.2 MGD cooling water make-up demand during peak power needs, with recycled water as the supply from the city's wastewater treatment plant. The demand is intermittent, only needed during peak power production, which led to some issues with residual chlorine levels that were too high, so a dechlorination process was added.

3.2.10 Potential for Recycled Water Use

Of the four energy sectors, the PHP sector includes the largest potential demand for recycled water use, as it represents the largest established industries with the highest water demands. The areas or types of projects in the PHP sector with the greatest potential for utilizing recycled water, in descending order of likelihood, are

- **New power plant projects** can be planned and designed for recycled water use, including the correct selection of alloys for cooling towers and conditioning and treatment to provide the needed water quality for cooling water make-up or boiler feed water. Also, new power plants enter the market for water at a disadvantage, so alternative supplies such as recycled water may be the only available option in quantities large enough to meet their demands.
- **Once-through cooling retrofits**. The SWRCB of California recently adopted a policy to phase out once-through cooling at all power plants in the state. The U.S. EPA is also considering a rule under the Clean Water Act, Section 316(b), to limit the use of open water intakes required by once-through cooling systems in order to limit deaths of fish and other aquatic organisms. Plants using once-through cooling will need to retrofit their cooling systems to meet the new requirements. Wet recirculating cooling towers are likely to be the most cost-effective solution, requiring a large-volume, reliable water supply. Recycled water can fill these needs, under the right circumstances. Plants with seawater intakes will find it expensive to select wet recirculating cooling tower equipment that is compatible with high-salinity seawater. PM10 limits set for cooling towers may also affect the ability to switch from seawater-fed, once-through cooling to recirculating cooling towers.
- **Switching water supply of existing plants**. Other existing plants with wet recirculating cooling towers may have specific drivers for switching water supplies. These could be increasing costs, regulatory pressure due to water scarcity, variable water quality of surface water supplies, or a variety of other reasons. Retrofit of existing plants encounters some challenges that may deter the use of recycled water, including incompatible alloys in the cooling towers, need for additional treatment, and others discussed in Chapter 4, Issues and Barriers.
- **Implementation of CCS**. Although CCS has not gained a foothold at power plants in the United States as of yet, if CCS facilities are installed at a site, the water demands will increase up to 40% over current operations. That magnitude of increase may require additional water sources to augment current supplies, and recycled water would be a feasible option. If regulations governing carbon emissions are put into

place, CCS-equipped power plants may be a growing potential source of expanded recycled water use.

Table 3.4 compares the relative opportunity for water reuse in each of the four categories described. The best opportunity for recycled water suppliers is to target new power plants near their service areas as potential users. New power plants will have the biggest challenges in finding a water supply source because of existing competition for water resources, so recycled water in sufficient quantities will be a good option for these plants.

To provide a sense of the scale of the most likely to be implemented potential recycled water users, Table 3.5 lists gross projections of potential water demands for the various power production categories, based on projections from the DOE. The increase in power production in each category is presumed to be met by new power plants as they are put online to meet the increased demands. These projected demands represent an estimate of the upper limit of potential water demands in the PHP sector.

Table 3.4. Opportunities for Water Reuse in PHP

Water Reuse Opportunity	Relative Quantity of Demand Opportunity	Likelihood of Implementation	Time Frame
New power plants	medium	high	near term
Once-through cooling facilities	medium	medium	near to mid-term
Water supply switch at existing plants	high	low	near to mid-term
Implementation of CCS	high	low	long term

The data in Table 3.5 represent an estimate for future potential water demands based on growth trends in the power industry according to the DOE. There likely exists potential for retrofitting some existing facilities to use recycled water as well, although that potential is highly dependent on site-specific conditions, regulatory requirements, and the comparative cost of existing water sources. For each category of power production in Table 3.5, actual water demand that could be met by recycled water is most likely much lower than that shown. In many cases, dry cooling will be used as the cooling technology, eliminating a large volume of potential water demand. In others, recycled water will simply not be economically or technically feasible as a result of local and site conditions.

Table 3.5. PHP Sector Projected Gross Recycled Water Demands

Category	Projected Energy Production (Million MWh/yr)		Potential New Water Demand (MGY)[1]	Potential New Water Demand (MGD)
	2011	2020		
Natural gas	1008	1109	26,000	71
Coal	1797	1743	--2	--2
Nuclear power	786	887	111,000	304
Geothermal	16	25	91	0.2
Biogenic municipal waste	14	15	240	0.7
Concentrating solar	1.1	3.0	1600	4.4
Solar photovoltaic	1.1	3.6	20	0.1
Total	**15,602**	**16,854**	**139,000**	**381**

Source: DOE, 2012
Notes: 1=the difference in the projected energy production between 2010 and 2020, multiplied by the water use factors listed in Table 3.1; 2=according to DOE, coal-fired electricity production is expected to drop slightly from 2011 to 2020, so no additional water demand is expected.

Regulators in areas with limited potable water supplies, particularly California, are beginning to view power plant cooling as less beneficial than other uses, such as domestic/residential and environmental (e.g., habitat) uses. Power plants utilizing once-through cooling systems are generally located near rivers, on the coast, or adjacent to other large bodies of water (e.g., reservoirs) but are alleged to cause excessive damage to nearby fish and wildlife. Should the regulations go into effect limiting once-through cooling, the cooling systems at these plants will likely be replaced with wet cooling tower systems, but they would face the problem of being located in areas with near fully allocated water supplies. Recycled water would be at the top of potential replacement water supplies, in these cases.

3.3 Biofuels Processing and Production

The BFPP sector includes all fuels produced from biogenic feedstocks to replace standard transportation fuels (e.g., gasoline and diesel). The current biofuels industry overwhelmingly consists of ethanol made from corn feedstocks, with biodiesel produced from crops and waste oils as a far second. However, the industry has a huge potential for growth, as indicated by the amount of private investment going into new biofuel start-up companies, government investment in both research and commercialization, and significant investment and research coming from established petroleum companies.

This section discusses the current status of the industry and attempts to capture the numerous new technologies being developed to produce biofuels and describe what water demands these new technologies will have.

3.3.1 Current Industry Status

Currently, commercial-scale biofuels production is limited to

- ethanol, mainly produced using corn as a feedstock, using either the dry- or wet-mill production processes; and
- biodiesel, produced through transesterification using oils derived from a variety of feedstocks, including soy, oilseed crops, and waste fats, oils, and greases (FOG).

Current ethanol feedstocks and production capacity are summarized in Table 3.6 and Figure 3.5. Biodiesel feedstocks and production capacity are summarized in Table 3.7 and Figure 3.6.

Table 3.6. Ethanol Feedstock Production Capacity at Currently Operating Facilities

Plant Feedstock	Capacity (million gallons/year)	No. of Facilities
Corn	14,226.0	193
Corn/milo	422.0	6
Corn/barley	65.0	2
Milo/wheat starch	48.0	1
Cheese whey	7.6	3
Beverage waste	5.4	1
Potato waste	4.0	1
Waste beer	3.0	1
Seed corn	1.5	1
Sugar cane bagasse	1.5	1
Wood waste	1.5	1
Waste sugars/starches	1.0	1
Brewery waste	0.4	1
Woody biomass	0.0	1
Total	**14,786.9**	**214**

Source: Renewable Fuels Association, 2011.

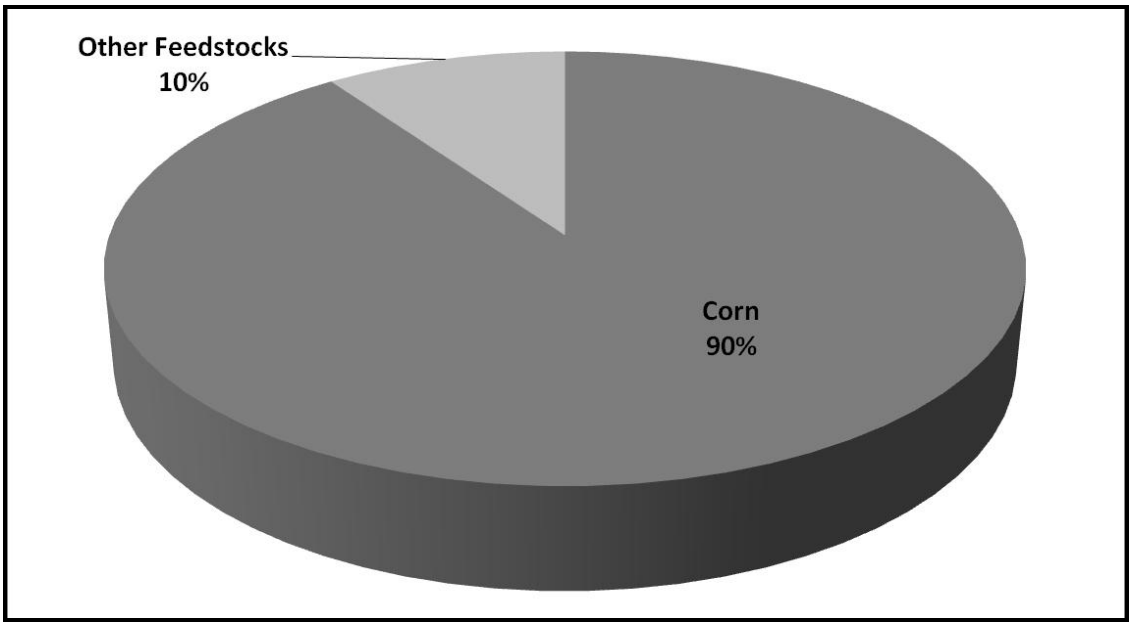

Figure 3.5. Percentage of operating ethanol facilities by feedstock.

Table 3.7. Biodiesel Feedstock Production Capacity at Currently Operating Facilities

Feedstock	Annual Biodiesel Production Capacity (million gallons)
Soy (multiple feedstock)1	1668.7
Soy	496.9
Oilseed crops	132.25
Waste oils, yellow grease, tallow	27.21
Palm	15.0
Feedstock not reported	63.9
Total	**2402.96**

Note: 1=Multiple feedstock facilities can produce biodiesel from many feedstocks but primarily use soy.

Source: National Biodiesel Board, 2011

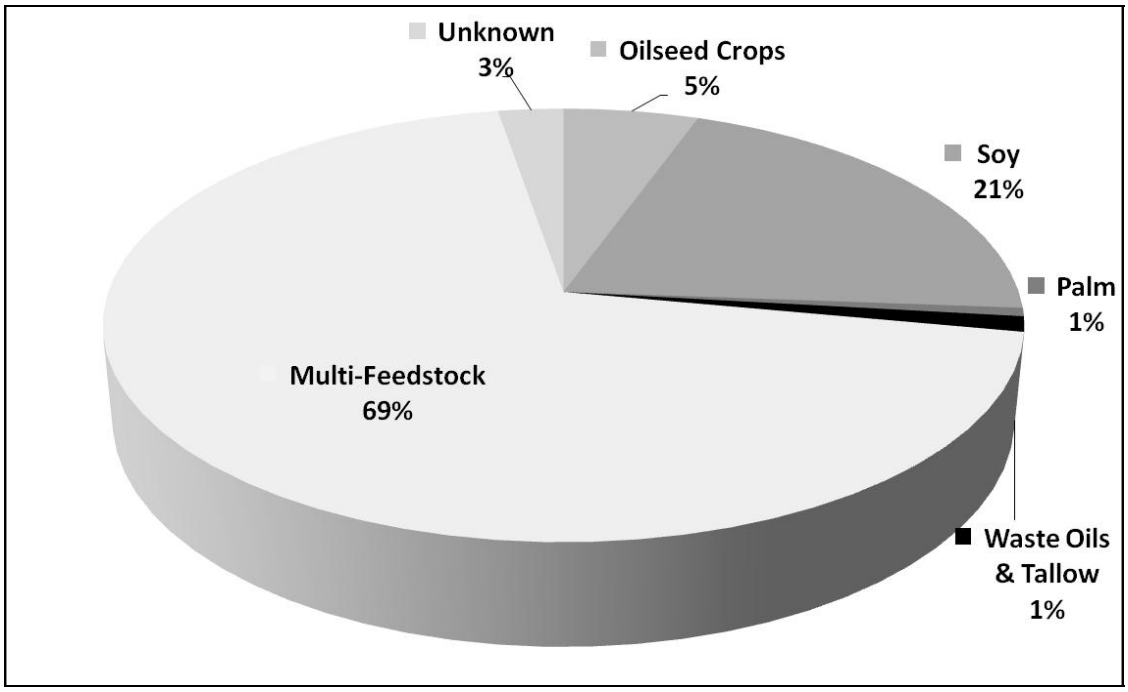

Figure 3.6. Percentage of operating biodiesel facilities by feedstock.

Source: National Biodiesel Board, http://www.biodiesel.org/buyingbiodiesel/plants/showall.aspx (last accessed December 2011).

Corn ethanol production in the United States has had exponential growth over the past 30 years, in particular during the last 10 years, as shown in Figure 3.7. Meanwhile, biodiesel is produced on a much smaller scale and production has fallen over the past three years after peaking in 2008.

Beyond the established commercial ethanol and biodiesel industries, there has been tremendous investment in research and development of other methods of producing biofuels. According to *Biofuels Digest,* an industry magazine, as of 2010 there were 39 pilot or demonstration-scale facilities in operation producing or researching advanced biofuels, precursors, and coproducts. Within 5 years, 105 facilities are projected to be in operation producing advanced biofuels, including commercial-scale facilities (*Biofuels Digest,* 2011). These planned facilities include the following production technologies:

- gasification of biomass
- Fischer-Tropsch (F-T) conversion from syngas to liquid fuels
- enzymatic hydrolysis
- fermentation
- algal oil extraction and transesterification of lipids to fuels

Of these planned facilities, more than 70% are projected to produce ethanol, with approximately 8% expected to produce biodiesel and 4% expected to produce renewable drop-in fuels, which are direct replacements for petroleum gasoline and diesel.

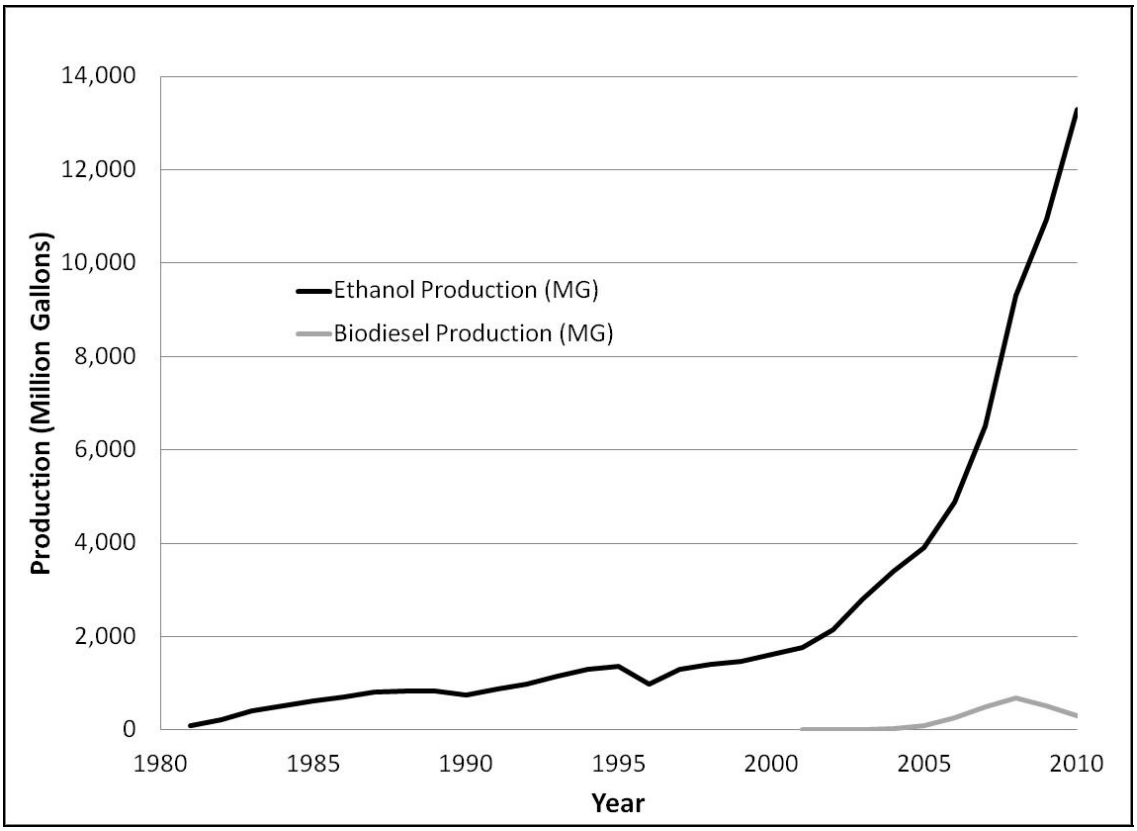

Figure 3.7. U.S. ethanol and biodiesel production (1981–2010).
Source: US EIA, 2011b.

3.3.2 Biofuels Production Processes

Within the categories of fuel product, the processes used to produce biofuels vary based on the feedstock source. Generally, the major feedstock-to-fuel processes include the following.

3.3.2.1 Ethanol—Corn Feedstocks

Ethanol is currently produced using corn as the primary feedstock. The process by which corn is converted to ethanol involves the following two steps:

- **Conversion of carbohydrates**. The first step in most biofuels production is conversion of the biomass feedstock to a form that is readily convertible to fuel. This processing step varies by feedstock. The complex carbohydrates are typically broken down to simple sugars through an enzymatic process specific to the type of carbohydrate (e.g., corn starch, lignocellulose). Some feedstocks only require physical processes to produce sugar solution, such as sugar cane and sugar beets.

- **Fermentation**. When a feedstock has been broken down into simple sugars, it can then be converted by fermentation into alcohol (e.g., ethanol, methanol).

To create ethanol from corn, the corn is processed by one of two ways: (1) dry milling or (2) wet milling. Dry milling is the more common method among commercial ethanol suppliers,

and it involves grinding the corn into corn meal, then combining it with water and enzymes to break down the starch into sugars. After that step, the sugars are fermented to create ethanol. In wet milling, the corn kernels are submerged in water and allowed to steep to separate the parts of the kernel, after which the starches are then converted to sugars using enzymes, as with dry milling. Following fermentation, the resulting ethanol is distilled to get it to the purity necessary to sell on the open market.

Because ethanol made from corn is the only widely established, commercialized method currently available, the associated water demands for the production of ethanol from corn are fairly well established (Wu et al., 2011). The primary water demands are

- grinding
- liquefaction (slurry water)
- fermentation
- separation
- drying

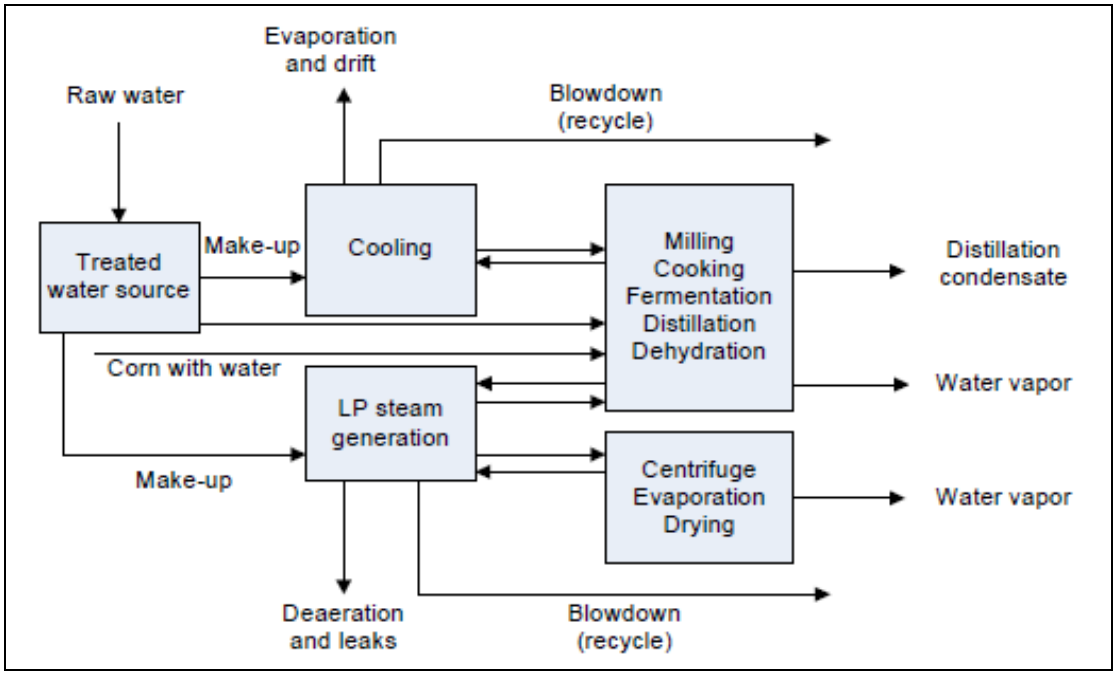

Figure 3.8. Water system in a typical dry mill ethanol plant.

Note: LP=low pressure
Source: Wu et al., 2009

Cooling tower make-up (53%) and drying (42%) account for most of the water consumption in the milling plant, with a typical dry mill plant consuming 3 gallons of water for every 1 gallon of ethanol produced in new facilities (Wu et al., 2009). Facilities constructed prior to 2000 can have higher water usage, at between 4 and 6 gallons per gallon of ethanol produced. However, process improvements indicate a reasonable average water use for older facilities is 4 gallons of water per gallon of ethanol produced, with about 60 to 70% of total water use for cooling water (MnTAP, 2008).

3.3.2.2 Ethanol—Sugar Crop Feedstocks

Other commercially established methods for producing ethanol from agricultural crops are with sugarcane or sugar beets; however, these feedstocks are not used widely in the United States. In both cases, sugar is physically extracted from the crop material, resulting in a sugar solution that can then be fermented. The process from unprocessed crop to sugar takes only one step, at which point the raw sugar can be converted to ethanol through fermentation. Market prices for sugar beets and sugarcane in the United States are generally high enough compared to corn that their cost precludes their use as a feedstock for ethanol production (Jacobs, 2006). In Brazil, where cultivation of sugarcane is more widespread, ethanol use replaces approximately 40% of the gasoline market for transportation. The cost per unit volume of ethanol produced from sugarcane in Brazil is estimated to be 42% less than the cost of ethanol production using corn in the United States (Goldember, 2008). It is not anticipated that ethanol production from sugarcane will expand in the United States, primarily because of its unsuitable climatic and hydrologic conditions.

3.3.2.3 Ethanol—Cellulosic Feedstocks

Production of ethanol using cellulosic biomass crops and crop wastes has been targeted as a source of biofuels with greater potential to displace petroleum without competing with food crops. However, the technologies to produce biofuels from cellulosic biomass sources are still largely in development. The time frame for this potential displacement is uncertain, because of a lack of established commercial-scale facilities in operation (NRC, 2008). Therefore, the potential for cellulosic ethanol production water demand is also uncertain in the near term.

The general processes involved in the production of biofuels from cellulosic biomass involve the following steps:

1. Breakdown of cellulosic biomass (cellulose) to component sugars via an enzyme-driven reaction
2. Conversion of sugars to ethanol via fermentation

Ongoing research is investigating methods to make the first step more cost effective. Expensive enzymes (cellulase) are required to break down the biomass to simple sugars. Although the process has been proven in pilot scale, it has not been proven to scale up to commercial level sufficiently to produce a steady, market-ready supply of ethanol.

Water use targets for commercial production of cellulosic ethanol are estimated to be similar or as much as 50% higher than those for corn ethanol, potentially requiring 6 gallons of water per gallon of ethanol produced. Current proven results, for processes with corn stover as the feedstock, fall in the range of 10 to 11 gallons of water per gallon of ethanol (Pate et al., 2007). As the process becomes commercialized, water use requirements are expected to drop

because of process efficiency improvements, with some industry targets set at less than 5 gallons per gallon of biofuels (Khosla, 2011).

3.3.2.4 Biodiesel

Biodiesel production is the second most prevalent and commercialized biofuel on the market. However, production of biodiesel is only approximately 3% of the size of the ethanol market. The feedstock used most frequently in the United States is soybeans, but a variety of other oilseed crops are utilized in smaller numbers for biodiesel production and have potential to become a larger share, including

- camelina
- rapeseed/canola
- safflower
- mustard/crambe
- sunflower
- palm oil
- jatropha

Biodiesel is also currently produced on the commercial scale using waste FOG from restaurants and animal processing facilities. These feedstocks and their characteristics are discussed more in Section 3.5, Biomass Feedstock Production.

The process for converting these feedstocks to biodiesel includes the following steps:

- Oil extraction. For oilseed crops, oil is produced through physical or mechanical extraction of the oil, sometimes referred to as expeller extraction, or through chemical extraction by solvents, typically hexane.
- Transesterification. Oil feedstocks (e.g., soybean oil, animal fats, and other vegetable oils) are primarily made of triglycerides (TAG), which can be converted to fatty acid methyl esters (FAMEs), otherwise known as biodiesel, by transesterification. This process involves mixing the source oil with alcohol (either ethanol or methanol) and a catalyst (usually sodium hydroxide or some other strong base). After reaction, the products are FAMEs and glycerol, which can be sold as a coproduct.

Water use in biodiesel production is approximately 25% to 33% less than that for corn ethanol, at only 1 gallon of water consumed per gallon of biodiesel produced, with a withdrawal demand of roughly 3 gallons per gallon (Pate et al., 2007).

3.3.2.5 Advanced Biofuels Production Technologies and Processes

Beyond the currently commercialized methods of producing biofuels, there are several emerging methods that have potential to produce biofuels at prices competitive to gasoline and diesel. These processes have been proven to work in other applications, but have not yet been established in the commercial market for transportation fuel production. Biofuels produced by these emerging methods have been dubbed “advanced biofuels” or “second generation biofuels.” The processes, broadly categorized as “thermochemical conversion” processes, are summarized as follows:

- Gasification is a process by which material with high carbon content reacts with steam at high temperatures to create synthetic gas (syngas), which is a mixture of carbon monoxide and hydrogen gas (with a small amount of carbon dioxide). This process can utilize a wide variety of carbonaceous feedstocks and has been used at full-scale coal power plants (i.e., IGCC plants) successfully for years, where the syngas is burned directly to produce power. For biofuels, biomass would be used as the carbon source for gasification, and the syngas would need to be converted via a catalyzed reaction into some form of liquid fuel. One promising avenue of research and development is to gasify sorted municipal solid waste (MSW) and then, through a catalytic process, convert the syngas into biofuels.
- F-T process. Following gasification, the F-T process is the catalyzed reaction that can convert syngas to diesel and a variety of other liquid hydrocarbons. This process has been successfully applied on a large scale in South Africa, Malaysia, and Qatar to produce diesel fuel from coal and natural gas. These established projects arose where an excess of one resource (coal or natural gas) existed in parallel to a shortage of another (petroleum).
- Hydrothermal gasification. Traditional gasification is not as compatible with biomass as a feedstock because biomass typically has high water content, so it must be dried prior to the gasification process in order to result in acceptable overall system efficiencies. An intriguing new line of research is in hydrothermal gasification, which transforms carbonaceous material in an aqueous solution to syngas by exposing the material to high temperatures and pressures so that the aqueous solution reaches a supercritical state. This process has not been commercially applied and is still in the research and development phase, but it holds great promise to produce biofuels from feedstocks such as algae, which have thus far proven difficult to process.
- Pyrolysis is the process by which carbonaceous material is converted to char and hydrocarbons by heating the material to high temperatures in the absence of oxygen. This process can produce so-called biocrude, which can then be refined to various biofuels. Using pyrolysis for biofuels production is still in the research and development phase, with some movement toward demonstration projects in the United States.

With respect to water use, it is estimated that thermochemical conversion will need less water than other processes (1 gallon of water per gallon of fuel or less), although this estimate has yet to be proven on the commercial scale (Khosla, 2011).

The various routes to producing biofuels are shown more comprehensively in Figure 3.9.

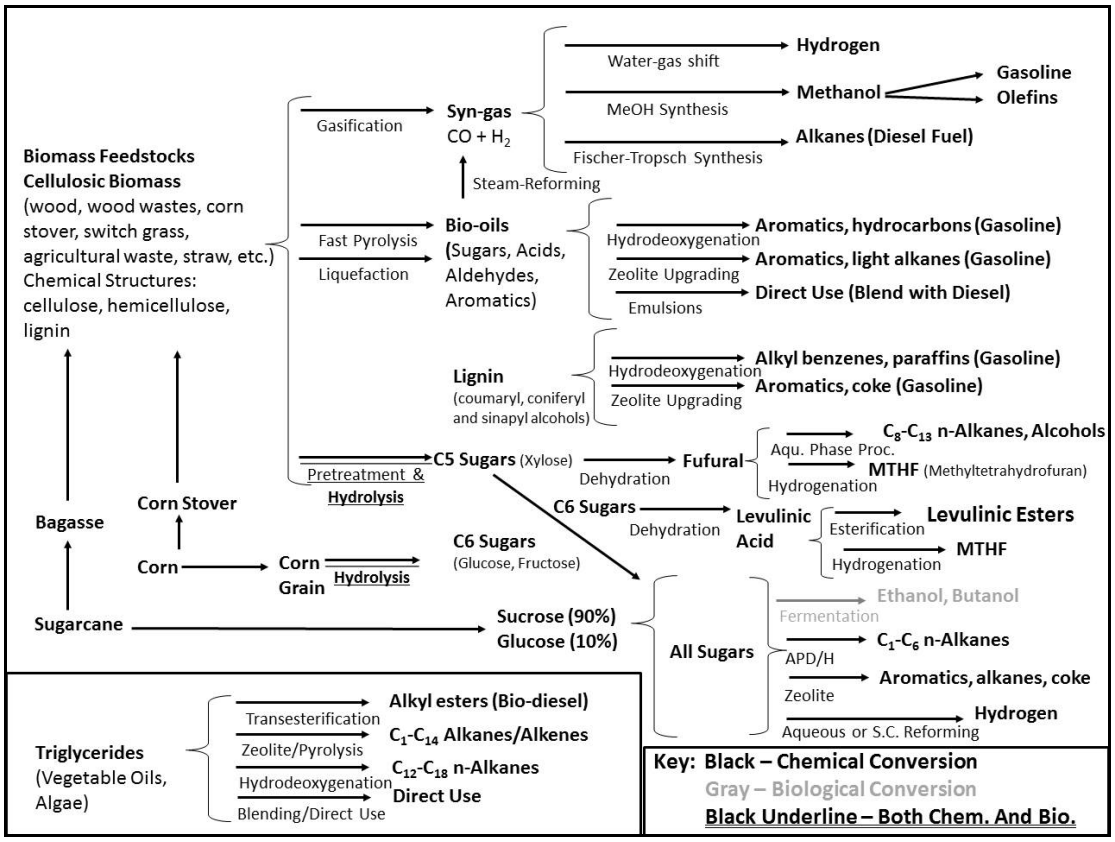

Figure 3.9. Feedstock-to-fuel methods of producing biofuels.

Source: NSF, 2008

3.3.3 Potential Water Demands

Water demands in the BFPP energy sector share similarities to those in the PHP sector, with the major demand being for wet cooling towers used as part of the refining processes. Unlike PHP, a good fraction of BFPP water demand is for process water: slurries, reaction media, wash down, and other needs. New facilities and most older facilities have incorporated treatment technologies so process water is recycled for cooling water and other consumptive uses. For the BFPP sector, the units for water use factors, shown in Table 3.8, are generally expressed in terms of gallons of water used per gallon of fuel produced but can also be expressed in terms of gallons of water used per unit of fuel energy (typically BTUs).

Table 3.8. BFPP Water Demands

Biofuel Type	Water Withdrawal Factor (gal H_2O/gal biofuel produced)		Water Consumption Factor (gal H_2O/gal biofuel produced)	
	NRC, 2008	Pate et al., 2007	NRC, 2008	Pate et al., 2007
Ethanol, corn based	4–7	6	--	4
Ethanol, sugar based	4–7	6	--	4
Ethanol, cellulose based	9.5 (est.)	3–12	--	2–6
Biodiesel	1–3	0.3–3	--	1

Ethanol produced from corn feedstocks is by far the most prevalent biofuel available today, and as a result the water demands associated with corn-based ethanol are the most established. Cellulose-based ethanol has not been fully commercialized on a large scale, so the efficiency of water use associated with its production has not been optimized. Existing data suggest that there is potential for increased water use efficiency as the technology matures.

Water demands associated with the cultivation of these crops is covered under the BMFP sector. In general, the move to cellulose-based ethanol is driven by the need to provide crops that require less irrigation and fewer chemicals for production, create less soil erosion when coupled with best management practices, and that do not compete with food-based market crops.

Biodiesel processing uses less water than ethanol processing because of its lower cooling water demands. The oil extraction process is similar across the various types of feedstocks; it typically requires that seeds be dry (less than 10% moisture content) to prevent mold growth and damage such as clogging of the extraction equipment.

It is difficult to project expected gross national water use in the production of biofuels because of the volatile market and uncertainty regarding commercialization of new technologies and expansion of existing technologies. Best estimates indicate that corn-based ethanol will continue to dominate the biofuels market in the next decade, with a notable increase in cellulosic ethanol production. Conventional biodiesel production will increase by four times its current production but will continue to be a small fraction of the total biofuels market.

As shown in Table 3.9, approximately 45 billion gallons per year of recycled water could be used to meet biofuel production water demands. Notably, the cellulosic ethanol industry's demand nearly matches that for corn ethanol. However, there is still great uncertainty with this new recycled water market. Cellulosic ethanol production technology is still emerging and needs to be cost competitive with corn-based ethanol production.

Table 3.9. Biofuels Production Water Use Opportunities

Biofuel Type	2010		2020		
	Biofuel Production (MG)	Water Withdrawal Demand Potential (MGY)	Biofuel Production (MG)	Water Withdrawal Demand Potential (MGY)	Likely Recycled Water Demand Potential (MGY)
Ethanol, corn and starch	14,677	88,000	18,521	111,000	23,000
Ethanol, cellulosic	0.25	2.4	2039	19,000	19,000
Biodiesel	460	1400	1614	4800	3000
Total		**89,400**		**134,800**	**45,000**

Notes: "Likely Recycled Water Demand Potential" refers to the difference between 2010 and 2020 "Water Withdrawal Demand Potential." Newly built plants are more likely to implement use of recycled water than existing plants, which would need to be retrofitted.

Source: US EIA, 2011a

Another source of potential water demands in the BFPP sector, although not yet quantified, is process steam for gasification of biomass. The gasification process requires high-quality (likely RO-treated) steam during the thermochemical conversion process. Several start-up companies are pursuing gasification conversion processes using biomass for eventual production of biofuels; however, information concerning the quantity of water required per volume of fuel production is not available at this stage in the development of the technology.

3.3.4 Water Quality Requirements

Because the BFPP and PHP sectors share many of the same water uses (e.g., cooling towers and boiler feed), water quality requirements follow similar guidelines. Tables 3.5 and 3.8 show requirements for cooling towers and boiler feed. Other process water uses are anticipated to require advanced treatment processes; however, it will depend on the specific recycled water quality. Given the high salt and hard waters typical in parts of the Midwest, treatment beyond tertiary filtration will be needed. For example, the Tharaldson ethanol plant in Casselton, ND, receives recycled water that is treated at Fargo's wastewater treatment facility with UF and RO processes.

Water quality requirements for specific biofuel process needs have not been publicly established beyond those for corn ethanol and conventional biodiesel production. Water for corn slurry must be purified (typically with RO treatment), although specific constituent limits have not been established industrywide (NRC, 2008). Much of the research relative to commercializing new biofuel production is being done in the private sector, and individual companies do not freely publish these data. However, it is expected that the water demands most compatible with recycled water use will be for recirculating cooling towers and therefore will have the same water quality requirements as those for power plant cooling towers. Boilers and process water will also be a potential source of demands for recycled water but will require high-purity water treated with microfiltration and RO.

3.3.5 Regional Considerations

Existing ethanol production facilities in the United States are more prevalent in the Midwest and Great Plains states, where corn cultivation is concentrated. This region does not have the broad-scale drivers for water reuse that other areas have. Although water is inexpensive and plentiful across much of the Midwest, there are regions with limited water supplies. Some biofuel production facilities have had to consider the available supply of water resources in siting of their plants. One of the 10 largest ethanol facilities in the country, Tharaldson Ethanol in Casselton, ND, uses recycled water. Fargo, located 26 miles away, provides the 150 MGY ethanol plant recycled water for its cooling and process water supply. The ethanol plant sends its cooling water blowdown and other waste discharges back to the Fargo wastewater treatment facility for final discharge to the Red River of the North. In this case, water supply scarcity required searching for a nontraditional source. Another consideration was the impact of reduced effluent discharge on the Red River of the North watershed.

With few recycled water applications and little regulatory framework for water recycling in the central United States, the use of recycled water in the biofuel production industry will take time to develop. As water reuse expands in the Midwest for other uses, it is expected that there will be more reuse in the biofuels industry. States such as Minnesota are providing financial incentives for water reuse. Legislation under H.F. 1231 in 2009 provided in-kind matching grants for capital projects incorporating water reuse, including specific funds targeting ethanol facilities. Even with incentives, it is not likely that water reuse projects will be implemented with many existing facilities, except perhaps in the more arid areas like North Dakota. Ethanol production facilities are frequently far from wastewater treatment plants that could provide recycled water. In a review of facilities in Minnesota, only 3 of 24 ethanol plants are within 2 miles of a wastewater treatment facility, and an available supply to meet all the demand of most ethanol plants was more than 10 miles away (Craddock Consulting Engineers, 2006.

Another issue for water reuse in the Midwest is the ability of the WWTF and the ethanol plant to meet discharge limits for salts. Some treatment technologies result in concentrated waste streams, and there is concern that pollutant concentration discharge limits (e.g., TDS, chloride, sulfate, boron, and specific conductance) may exceed the water quality standards for some receiving streams. There are existing industries that cannot expand operations because they cannot reduce salt concentrations in the discharge cost effectively and meet their NPDES permit requirements. Recent requirements for monitoring salty discharges at municipal WWTFs in the Midwest indicate that permit limits may be forthcoming for parameters that some facilities cannot currently achieve. The incorporation of recycled water practices may increase salt concentrations in the WWTF effluent and become a deterrent to water reuse at some facilities.

3.3.6 Opportunities for Recycled Water Use

The biofuel production industry is a viable customer for recycled water. As with the PHP sector, the most likely opportunities for meeting water demands with recycled water will be from new facility construction. Established plants will not likely see an advantage to changing or supplementing water supply sources except where there are strong drivers. The most immediate driver will be for locations without a sufficient water supply, as described for the Tharaldson ethanol plant in North Dakota. Economic development, water supply limitations, and environmental regulations and stewardship will increasingly drive the need to find alternative water supplies. Looking to balance income from water supply and the need to

build more infrastructure, communities can partner with local industries such as biofuel production facilities to provide conditions where water reuse can provide environmental benefits and economic advantages for all partners.

The emerging biofuel production technologies present excellent opportunities for incorporating water reuse with commercial facilities; these opportunities are summarized in Table 3.10. The location of production facilities can be planned with a community's wastewater treatment infrastructure improvements. Many municipal facilities are aging and require improvements to meet new regulatory requirements. The areas to grow new feedstock can be selected based on a balance of irrigation, production location, and longer-term climate factors. The future of the biofuel production industry presents an opportunity for regional partnerships to integrate water resources, energy, and economic growth.

3.4 Bioenergy Processing and Production

The BEPP sector shares many of the same technologies as in the previous two sectors, PHP and BFPP, and generally includes those industries and technologies that produce electrical energy from biogenic fuel sources, such as

- Co-firing of biomass with fossil fuels
- Direct firing
- Gasification of biomass for power generation
- Pyrolysis for power generation
- Anaerobic digestion
- Biogas production from municipal waste

The BEPP sector overlaps heavily with PHP in that both sectors involve power generation, although BEPP power generation strictly involves the use of biomass or biomass-derived fuels. BEPP overlaps with BFPP in that many of the emerging technologies being researched for biofuels production, such as gasification and pyrolysis, are also used to produce electricity.

Table 3.10. Opportunities for Water Reuse in BFPP

Water Reuse Opportunity	Relative Quantity of Demand Opportunity	Likelihood of Implementation	Time Frame
New ethanol production plants	high[1]	medium–high	near term
New biodiesel production plants	low	medium	near term
New advanced biofuels production plants	high[1]	uncertain	mid- to long term
Water supply switch at existing plants	medium[2]	low	near to mid-term

Notes: 1=Best opportunity is in the planning stages when siting facilities; need population centers with adequate supply in proximity. 2=Emerging opportunities for facilities near larger population centers to coordinate with municipal wastewater treatment improvements to meet impending nutrient removal discharge limits

3.4.1 Co-Firing and Direct Firing of Biomass

Co-firing is the term for substituting a portion of fossil fuels used for power generation with biomass as part of standard thermoelectric power generation. Facilities currently co-firing with biomass are all coal-fired plants modified slightly to use a portion of biomass. The boiler and power station are the same as for a conventional coal-fired boiler, and in most cases the biomass is co-fired in the same boiler as the coal.

Biomass co-firing power plants have been in operation for decades and, according to the Oak Ridge National Laboratory Biomass Energy Data Book, there are currently 161 facilities in the United States that utilize biomass as part of either a co-firing or direct firing operation (Oak Ridge National Laboratory, 2010). Most commonly, these facilities burn wood or wood products in a boiler, very similar to fossil fuel power plants; however, the energy density (energy per unit weight) of biomass is much less than that of fossil fuels, so transporting biomass any great distance (more than 20 miles) is not cost effective given the cost of shipping. Therefore, the location of biomass co-firing and firing facilities is typically selected based on the availability of biomass fuel. For example, many of the existing facilities are co-located with wood or paper mills where woody waste or paper byproducts are readily available and in need of disposal. The process known as torrefaction (discussed in another section) can improve the characteristics of biomass to make it more compatible with co-firing, improving thermal efficiency and making the biomass more easily transportable to co-firing power plants.

Direct firing uses strictly biomass as fuel for power generation rather than a combination of biomass and fossil fuel. Typically, direct-fired, biomass-fueled power plants have lower capacities (20–50 MW) than coal-fired plants (100–1500 MW) because the energy density of the biomass fuel is so low that to fuel a large-capacity power plant would require vast quantities of biomass, which is not feasible in most circumstances.

3.4.2 Gasification

Gasification is a process by which material with high carbon content reacts with steam at high temperatures to create syngas, which is a mixture of carbon monoxide and hydrogen gas with a small amount of carbon dioxide and other impurities, depending on the temperature. Gasification has been successfully used with coal as the fuel in IGCC power plants, but biomass can be utilized as the fuel as well. Figure 3.10 shows a schematic diagram of an IGCC power plant using biomass as the fuel.

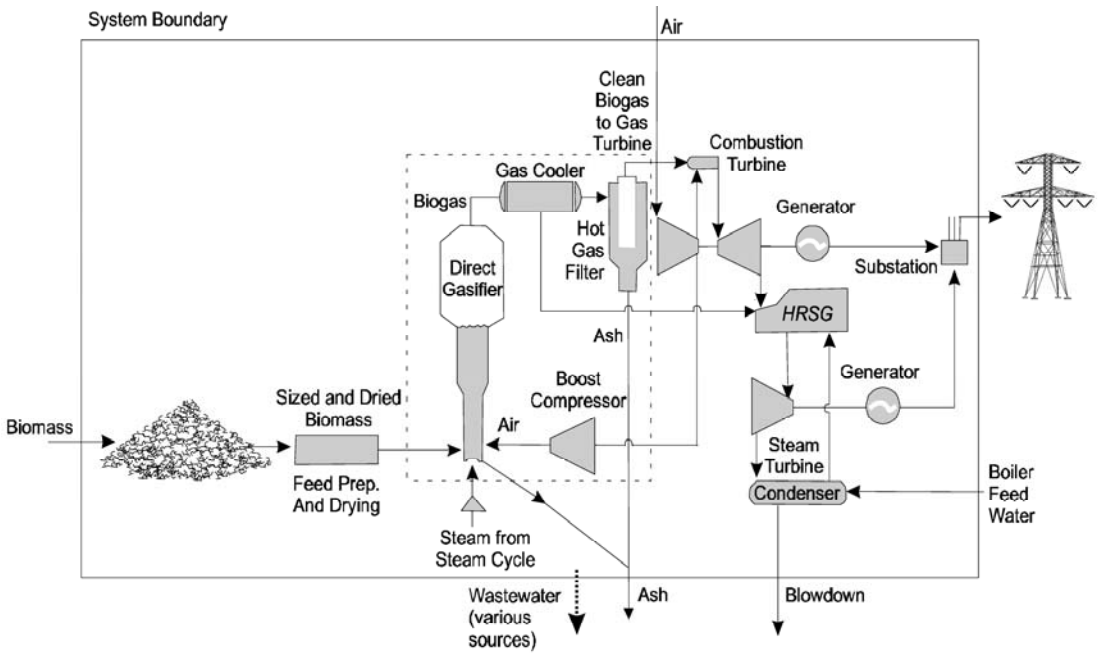

Figure 3.10. Biomass integrated gasification combined cycle power plant schematic.
Source: US DOE and EPRI, 1997.

Primenergy is a private company that produces gasifiers used in biofuels operations, including one in Little Falls, MN, at a facility for the Central Minnesota Ethanol Cooperative. A process flow schematic is shown in Figure 3.11. The gasifier receives biomass in the form of waste wood and crop residues to create syngas, then the system combines the syngas with distillers' dried grains with solubles, a byproduct from the corn ethanol production process. The overall system produces electricity to power the ethanol production process and provide heat to the system.

The Little Falls plant represents a good example of how biomass gasification technology implementation will likely spread: where low-cost feedstocks are available locally in large quantities, the operating costs of gasification can be kept low. Co-locating the gasifier at an ethanol plant also increases efficiency by utilizing waste heat, a configuration that can be duplicated at other locations that generate large amounts of biomass. When it is used to produce electricity, biomass gasification is essentially the same process relative to cooling water make-up and gasification process water demands as coal IGCC, as listed in Table 3.1.

Gasification can, in theory, use any form of biomass, from agricultural residues to MSW to biosolids from municipal wastewater treatment; however, it has been proven on the commercial scale primarily for fuel wood and woody wastes. Each feedstock has different characteristics and must be processed and handled differently to maximize gasification process efficiency. These methods of processing and handling have not been established on the commercial scale. Low-cost biomass feedstocks like MSW and biosolids could provide an incentive to implement gasification facilities, but high capital and operating costs increase the risk that these projects will not be profitable, and so wide implementation has not occurred yet in the United States (EPRI, 2011).

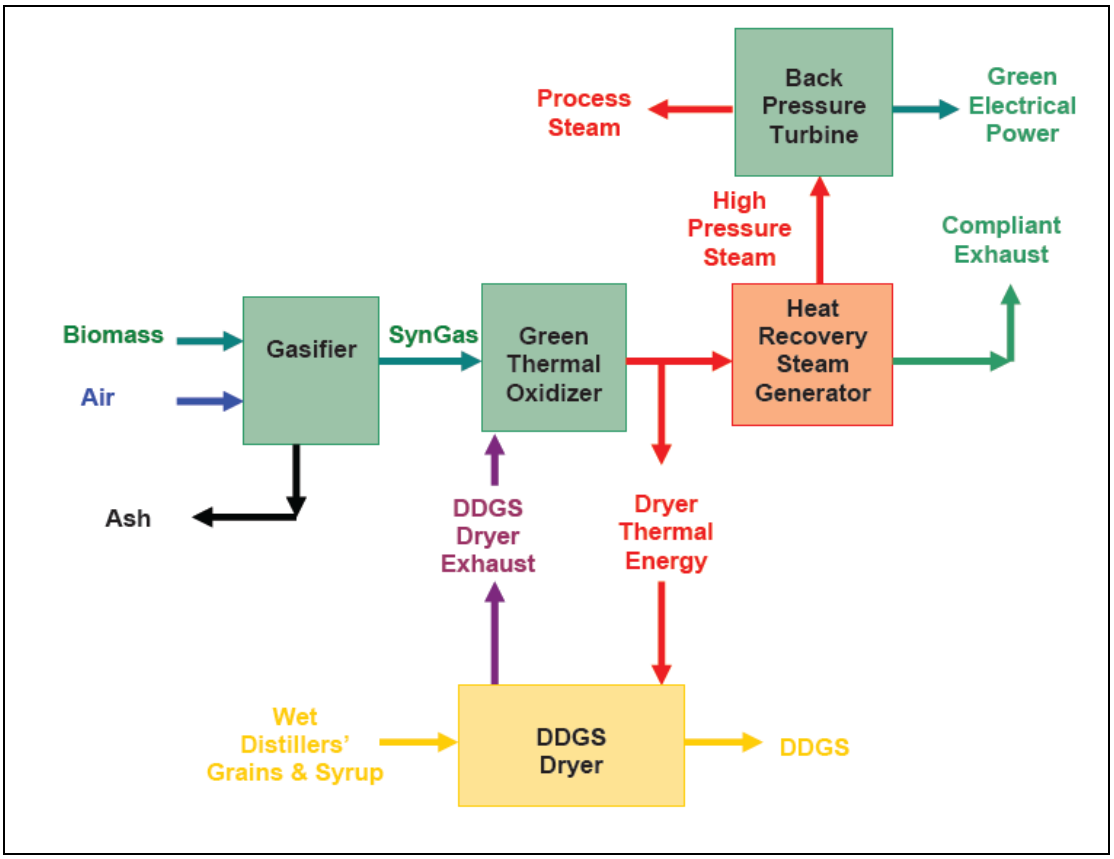

Figure 3.11. Process flow schematic for Primenergy Little Falls gasifier system.
Source: Primenergy, LLC, 2006

3.4.3 Pyrolysis and Torrefaction

Gasification, pyrolysis, and torrefaction are a spectrum of thermal conversion processes occurring in the absence of oxygen at varying temperature ranges. Pyrolysis is a process that, like gasification, converts carbonaceous material such as fossil fuels or biomass at high temperatures (400–800 °C) in the absence of oxygen. The product is known as pyrolysis oil, which is similar in characteristics to No. 4 fuel oil, but also produces gas and charcoal byproducts. Pyrolysis occurs at lower temperatures than gasification. The advantage of pyrolysis is that the product oil can be refined in a similar manner to crude oil, resulting in products equivalent to current petroleum products such as gasoline and diesel. However, pyrolysis oil has a higher acidity than petroleum crude, so it must be treated to be compatible and fully miscible with traditional crude. Pyrolysis oil can also be burned directly as fuel oil would be for heat or electricity (EPRI, 2011).

Torrefaction is a process that has promise to increase the effectiveness of co-firing that occurs in temperatures slightly lower (200–360 °C) than those required for pyrolysis. It converts carbonaceous material, including biomass, to a char with higher energy density, less moisture content, and less susceptibility to decay than raw biomass. These characteristics can make biomass more readily transportable; however, any cost savings is counterbalanced by the increased cost added by the torrefaction process (EPRI, 2010). Torrefaction, like pyrolysis and biomass gasification, has not been established on the commercial scale, so implementation opportunities are uncertain.

3.4.4 Anaerobic Digestion

Anaerobic digestion is the degradation of organic material by bacteria to product biogas (a mixture composed mainly of methane and carbon dioxide) and biosolids. Anaerobic digestion utilizes biomass in the form of sludge from municipal wastewater, animal wastes, or other aqueous, high–organic solid content biomass. It is common at wastewater treatment plants and can also be found at facilities that house large populations of animals (e.g., dairies, feed lots, poultry farms). The biogas is collected and combusted to create electricity via some type of generator. Most commonly, the biogas is burned in an internal combustion engine (engine generator), but other options include microturbines and fuel cells.

The anaerobic digestion process does not require an additional source of water, as the input to the process is settled sludge from the wastewater treatment process or agricultural animal wastes. The settled sludge consists of mostly water and, in fact, the processes following anaerobic digestion to prepare the solids for disposal require further dewatering, which creates a waste stream of water that is typically recycled within the plant. Cooling towers are not required for the biogas combustion and power generation process; however, wastewater treatment plants utilize CHP technology to capture waste heat from the process of burning biogas and use that heat to raise the temperature of the anaerobic digesters, which enhances the biological processes in the digesters and increases biogas production. The CHP systems do not typically need a large volume of continuous make-up water, as they are closed loops and only need to be replenished when losses or leaks occur in the piping system.

In a dairy, feedlot, or other animal operation that produces sufficient animal waste, anaerobic digestion can also be utilized to produce biogas. Operations that house animals in close quarters indoors, such as dairies, hog farms, and chicken farms, can collect animal waste with wash down water and convey the waste to anaerobic digesters to produce biogas. One potential water demand that could easily be met with recycled water is wash down water. One source indicates that the water demand for wash down at dairies is approximately 100 gallons per cow per day (Burke, 2001), so dairies with 1000 cows could potentially have a water demand of 0.1 MGD each. Not all dairies are of the right size or have the right site conditions for implementing anaerobic digestion, and dairies are often far from population centers where wastewater is treated, so a combination of factors has to match up well for recycled water use as wash down water at a dairy to become feasible.

EPRI (2004) performed a market assessment of the potential for anaerobic digestion in the agricultural sector and found that most existing digester systems at agricultural facilities burn the biogas in internal combustion engines, with one microturbine implemented at a hog farm. Neither of these configurations require cooling water (microturbines are typically air cooled), so opportunities for recycled water use in the power generation process are not frequent , although both engines and microturbines can be used in CHP systems that would require a small water demand to replenish the closed-loop, heated water system. In fact, CHP would be advantageous at these types of facilities to heat the digesters and improve biogas production, but the consumptive water demand would be fairly low.

3.4.5 Landfill Gas

Landfill gas is created through biological processes similar to those found in anaerobic digestion. Organic material is biologically degraded with carbon dioxide and methane as byproducts. Landfill gas is collected and then burned in energy-generating facilities similar to those of anaerobic digesters, either engine generators, microturbines, or fuel cells. These

facilities typically do not have cooling towers, so cooling water make-up demand is not likely.

Water is not necessary on any large scale at landfills, so the opportunities for recycled water use are slight. In addition, landfills often collect leachate and could potentially use that water for nonpotable uses, if sufficient treatment is implemented.

3.4.6 Potential Water Demands

Water demands in the BEPP sector are similar in type and intensity to PHP demands. Cooling water is the primary demand in terms of quantity, with boiler feed a remote second (roughly 10% of cooling water demand for wet recirculating cooling towers). Current biomass-fired power plants and co-firing plants do not have additional significant water demands, as the biomass fuel needs to remain as dry as possible for most efficient burning. Biomass gasification plants have similar magnitude, high-quality water demands to coal IGCC plants.

According to EIA projections for electricity generation, direct firing of biomass is expected to remain relatively level during the next 25 years, while co-firing is expected to increase dramatically. Table 3.11 provides an estimate of the potential growth and water demands associated with that growth. EIA does not specify electricity generation from gasification of biomass in its projections, so the projections shown here are subject to modification as the technology matures.

With the expected growth in co-firing over the next 25 years, the most likely source of potential recycled water demands are in that area. Direct firing is not expected to grow, so new plants will be limited in the coming years; however, it should be noted that co-firing occurs in coal-fired power plants. The projections in Table 3.11 represent the fraction of power resulting from biomass burned but not necessarily new plants that have been built to co-fire biomass and coal. As states across the country implement renewable energy standards, more plants are expected to opt for biomass for a portion of their fuel needs as an alternative to coal.

3.4.7 Potential for Recycled Water Use

Water demands in the BEPP sector are very similar to PHP in terms of quantities per unit of energy produced and quality requirements. Fuel source and quality of that biomass, in terms of energy density and water content, affect the thermal efficiency and therefore power generation of the plant, so the actual water use will depend on project-specific characteristics. Table 3.12 shows the water demand estimates for biomass power generation. The uncertainty of commercial implementation of bioenergy power production technology limits the potential near-term opportunities for recycled water at these facilities.

3.5 Biomass Feedstock Production

The term “biomass” generally refers to raw materials that have been derived from biological sources, such as plants or animals. “Biomass feedstocks” refer specifically to a supply of biomass-based raw materials that can be used for the production of energy or fuels. Biomass feedstocks include

- agricultural crops (e.g., corn, soybeans, sorghum, oilseed)

- agricultural residues (e.g., corn stover, bagasse)
- woody waste (e.g., logging debris, wood chips)
- algae
- MSW
- waste grease or FOG
- biosolids (from municipal wastewater)

Table 3.11. Bioenergy Production Water Use Opportunities

Bioenergy Type	2011		2020		
	Electricity Generation (MWh)	Water Withdrawal Demand Potential (MGY)	Electricity Generation (MWh)	Water Withdrawal Demand Potential (MGY)	Likely Recycled Water Demand Potential (MGY)
Direct firing	8,960,000	7867	13,160,000	11,554	3700
Co-firing[1]	1,400,000	1407	38,440,000	38,632	37,200
Total	10,360,000	9274	51,600,000	50,187	40,900

Note: EIA classifies co-firing power plants as those that burn natural gas in conjunction with another fuel. Power plants that co-fire coal with another fuel are categorized as coal power plants. Water withdrawal factors are also shown in Table 3.1.

Source: US EIA, 2012.

Table 3.12. Opportunities for Water Reuse in BEPP

Water Reuse Opportunity	Relative Quantity of Demand Opportunity	Likelihood of Implementation	Time Frame
New direct firing plants	low	low	N/A
New co-firing plants	medium	medium	mid- to long term
Dedicated gasification plants	uncertain	medium	mid- to long term
Anaerobic digestion at dairies	low	medium	near term
Landfill biogas-fired power facilities	low	low	N/A

These biomass feedstocks can be utilized in a variety of applications, including production of various biofuels, conversion to syngas by gasification, digestion and conversion to biogas, direct combustion, and combinations of these processes. This section discusses the biomass feedstock sources, current availability, growth potential, and associated water demands in their production.

3.5.1 Agricultural Crops

There are a wide range of traditional agricultural crops with potential to be used as biomass feedstocks. These crops are used as the raw materials for producing biofuels. The crops can be broken down into two major categories: (1) carbohydrate (sugar) based and (2) lipid (oil) based.

Carbohydrate-based biomass crops are typically used in production of biofuels consisting of alcohols, most commonly ethanol but also methanol and butanol. The crops used include

- corn
- sugarcane
- sugar beets
- sweet sorghum
- switchgrass (cellulosic)

Of these crops, corn production in the United States is vastly greater than the other crops. According to the U.S. Department of Agriculture (USDA), as of the 2011 commodity market year, approximately 37% of total corn production (on a per million bushel basis) was used for ethanol production (USDA, 2011). The percentage of corn used for ethanol production has increased steadily in the past few years from 23% of all corn grain in 2007 to 37% in 2010. However, the USDA expects this percentage to fall back to between 33% and 34% in the next ten years and remain steady.

Sugarcane is largely a tropical or subtropical crop, so production in the United States is limited to southern Florida, Gulf Coast Louisiana, southern Texas, and Hawaii. The acreage compatible to sugarcane cultivation in the United States is limited and not capable of growing to accommodate increased biofuels production. Sugar beets are primarily grown in the upper Midwest (Minnesota and North Dakota) and Great Plains states. Current and recent historical sugar prices in the United States tend to cause sugarcane and sugar beets to be grown for food sugar rather than as a feedstock for biofuels. Sweet sorghum has been identified as a potential alternative to corn and sugar crops to produce ethanol.

Lipid-based biomass crops are typically used in production of biodiesel. Seeds from these crops are processed to produce a raw oil, which is then processed further to produce biodiesel. These crops, typically referred to as oilseed crops, include

- soybeans
- rapeseed/canola
- safflower
- mustard
- camelina
- sunflower
- jatropha
- palm oil

- coconut

Soybeans are currently the largest volume crop in the United States used for making biofuels out of these oilseed varieties; approximately 43% of all biodiesel produced in the United States originates from soybeans. This fraction has dropped in recent years as other feedstocks, in particular waste FOG, have become more prevalent. The gross level of soybean production going to biodiesel production is expected to level off, whereas the use of FOG will increase as it is the low-cost alternative. Other oilseed crops are not expected to compose much of the total percentage of feedstock used to make biodiesel, as the cost of their inputs relative to soybeans is much higher, making them less competitive in the feedstock marketplace.
Figure 3.12 shows projections for soybean biodiesel production, as well as the level of federally mandated biodiesel production (U.S.DOE, 2011).

All oilseed crops have potential as biodiesel feedstocks; however, most of these crops are currently used primarily for production of food-grade oils that sell at a higher price than is competitive for biofuel feedstocks. For that reason, soy dominates the market for biodiesel feedstocks in the United States. Camelina has been identified as a potential dedicated energy crop for production of biodiesel. It has a few advantages over other oilseed crops, as it does not have as high an irrigation demand as soy and is not currently used for food-grade oil products, so the price would not be influenced by competing uses.

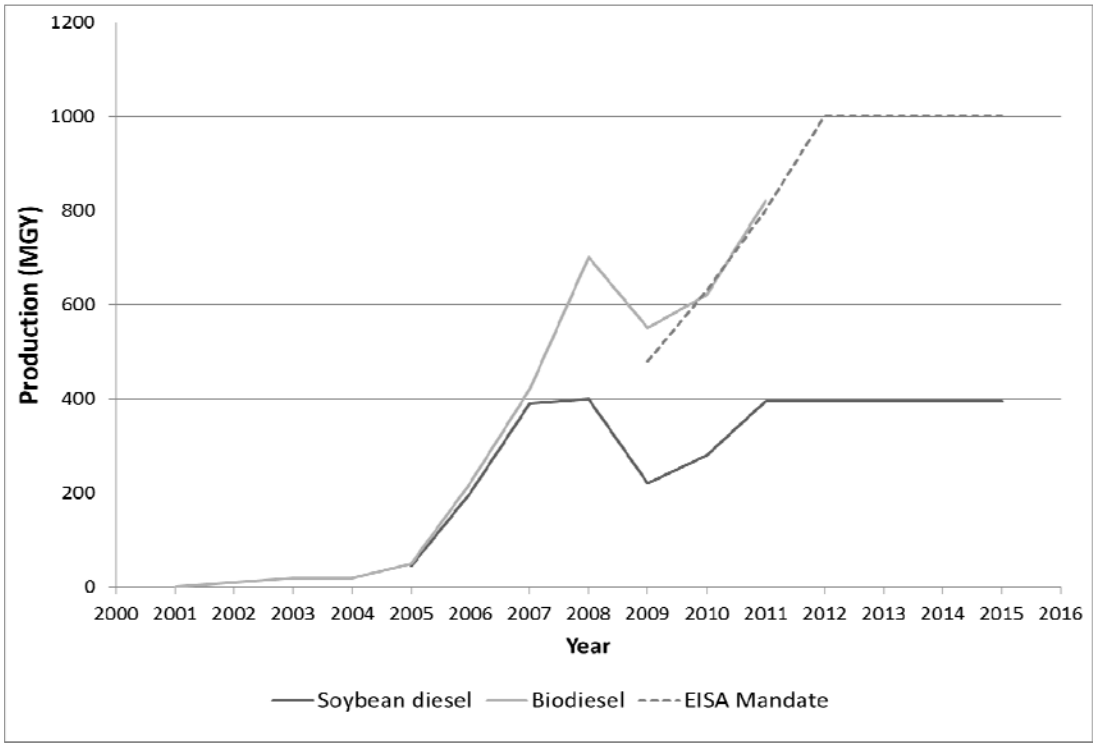

Figure 3.12. Projected soybean biodiesel production.
Note: EISA refers to the Energy Independence and Security Act, which increased the federal Renewable Fuels Standard. It calls for the production by 2022 of 36 billion gallons of renewable fuel with specific targets for greenhouse gas reductions.
Source: U.S. DOE, 2011

3.5.2 Agricultural Residues

Agricultural residues are byproducts of crop production and include the herbaceous material left behind after harvest as well as the remaining material, such as corn cobs or wheat husks, after crops have been processed. These materials are potentially valuable for cellulosic ethanol production; the stalks, leaves, and other residues can be broken down into starch, then converted to ethanol or potentially gasified and converted to other fuels.

The Oak Ridge National Laboratory has conducted a wide-ranging study of biomass availability in the United States, first in 2005 and updated in 2011 (U.S.DOE, 2011). This study has estimated the availability and projections for several common agricultural residues.

- Corn stover currently represents the largest single source of potential agricultural residues, at between 170 and 256 million dry tons, only part of which is actually available as a feedstock because farmers need to retain some to minimize nutrient loss from their soil. Availability may double during the next 10 years, depending on the price paid (the higher the price, the more is expected to be available for sale).
- Wheat, oat, and barley straw and grain sorghum stubble residues are currently about one-third of the total tonnage of corn stover available and would follow a similar increase in availability in the next 10 years.

Other residues such as sugarcane bagasse, orchard and vineyard prunings, cotton field and gin residues, and rice hulls can be used in a similar manner as corn stover but are much more limited in quantity. Bagasse is commonly used for fuel at sugar processing plants; however, sugarcane production is limited in the United States, so it is not produced in large quantities.

Agricultural residue availability is highly sensitive to price; farmers essentially make a tradeoff between leaving the stover or straw in their fields to degrade and replenish their soil or selling the residues and applying fertilizer to provide more nutrients. The price of these residues for biofuel and bioenergy production will be driven by what technologies are successful and commercialized, so until these issues are sorted out, the availability of agricultural residue biomass is uncertain.

3.5.3 Woody Wastes

The timber industry produces a large quantity of woody wastes during harvest and the milling process. Woody wastes can be used both as a fuel, as in biomass direct and co-firing, and as a feedstock for producing other fuels. For the most part, woody wastes do not have a water demand as part of production as they are a byproduct of timber, which is generally not irrigated. The market for woody wastes has not been developed because of lack of demand, and estimates of how much would be available, given harvesting technologies, are highly uncertain and dependent on price. A lack of recognized water demand during production and the highly uncertain future availability of this feedstock mean that woody wastes are not a major potential opportunity for recycled water use.

3.5.4 Waste Grease and FOG

Waste grease and FOG include tallow (rendered animal fat), lard (white grease), poultry fat, and yellow grease (waste cooking oil). These sources can all be used as feedstocks for

biodiesel production or, less commonly, can be burned directly for energy. This class of feedstock materials has a current market outside of biofuels or bioenergy, as food products, animal feed, consumer products, or other uses. In some cases, waste grease and FOG have been used in anaerobic digesters to enhance biogas production for energy generation. East Bay Municipal Utility District in Northern California has exploited the possibilities of using waste grease and FOG for biodiesel production at its main wastewater treatment plant.

The DOE has projected that widespread use of waste grease and FOG for biofuels or bioenergy use will not proliferate because of the competing uses for these materials in other market segments and the continued high cost relative to competitive costs for biofuels and bioenergy (U.S.DOE, 2011). In addition, waste grease and FOG feedstocks (primarily biodiesel) do not require water during production; in fact, water can lower their value and must be removed if possible. Therefore, no major opportunities exist for recycled water use in production of waste grease and FOG feedstocks.

3.5.5 Algae Feedstocks

The feedstock that has the most theoretical potential, in terms of yield or biomass per acre, is microalgae. Microalgae grow fast, can grow in brackish or otherwise low-quality water, and can produce lipids in high quantities relative to their total mass, depending on the species.

Modest efforts have been made since the 1940s to harness the high productivity of microalgae, specifically through wastewater treatment and the production of food, feed, fuel, and fine chemicals (Caldwell, 1946; Burlew, 1953; Oswald and Golueke, 1960). The first large-scale, outdoor microalgae production ponds were established in 1953 in Japan to cultivate *Chlorella* as a food supplement (Benemann and Oswald, 1996). Since then, the commercial microalgae industry has grown to produce roughly 10,000 tons per year worldwide, mainly as nutritional supplements (Benemann, 2009). At the same time, algae have been recognized as a potential source of fuel, primarily liquid transportation fuel or biogas. After the oil shocks of the 1970s, the DOE funded the Aquatic Species Program, an extensive 17-year study that began to quantify the requirements for large-scale production of microalgae-derived liquid biofuels (Sheehan et al., 1998).

The current need to reduce greenhouse gas emissions and improve energy security has revitalized interest in renewable sources of transportation fuels. Microalgae have re-emerged as a promising fuel feedstock as focus has begun to shift away from terrestrial crops that compete with food production for land, water, and fertilizer. Notable advantages of microalgae cultivation are that it does not require agricultural land or fresh water. The other stand-out advantage of many microalgae species is their fast growth rate compared to traditional crops and the oil content of certain species, which has been reported to be in excess of 75% of dry weight (Chisti, 2007).

In order to achieve their peak productivities, microalgae require large quantities of nutrients and enriched sources of carbon dioxide. To be competitive with the petroleum industry, microalgae must be produced at a very large scale and at low cost. Therefore, synergy with wastewater treatment (providing nutrients and water) and electric utilities (providing carbon dioxide) is advantageous for supplying these needed resources and can possibly offset costs.

Given the right mixture of nutrients, exposure to light, proper temperature, carbon dioxide, and water to grow in, microalgae have the potential to exceed the areal oil productivity of soy by 40 times. Reasonable projections of oil production range from 1000 to 3000 gallons per

acre per year, with 4500 gallons per acre per year being the theoretical maximum. Optimizing microalgal growth to achieve high oil yields requires an understanding of the key biological and engineering parameters that need to be controlled.

Microalgal biomass production for triglycerides (TAGs) requires three main steps: cultivation, harvesting, and biomass processing. The systems for the cultivation step must be designed to provide the basic growth requirements for microalgae. As described previously, these are nutrients (primarily nitrogen, phosphorus, iron), light (with some exceptions), carbon dioxide, and water. Temperatures in the range of 20 to 30 °C are favored by many high-productivity species (Dauta et al., 1990). In addition, inhibitors to high productivity must be controlled, such as excessive dissolved oxygen, pathogens (viruses, infective fungi), and grazing zooplankton (*Daphnia*, rotifers). The main categories of cultivation technology range from simple and relatively inexpensive to high tech, as shown in the following list:

- Open pond systems
  - ✓ usually paddle wheel–mixed raceway or "high rate" ponds
  - ✓ depths of 20–100 cm
  - ✓ common in current commercial algae production
  - ✓ a few wastewater treatment plants in the United States use high rate ponds.
- Closed photobioreactors (PBRs)
  - ✓ thin culture vessels that promote dense cultures
  - ✓ culture thickness of 2–15 cm
  - ✓ many designs and materials used
  - ✓ rare in commercial algae production
- Closed and open hybrid systems
  - ✓ use PBRs to produce inoculum for open ponds
  - ✓ routine inoculation used currently for commercial Chlorella and Haematococcus production
- Heterotrophic fermentations
  - ✓ algae capable of heterotrophy grown in the dark in sterile tanks using sugars as the carbon and energy source
  - ✓ currently used commercially for high-value nutritional fatty acids
  - ✓ probably an inefficient source of fuel energy because of its use of fixed carbon substrate
- Algal turf scrubbers
  - ✓ filamentous and biofilm algae grown on channels with sheet flow of media
  - ✓ water depth of 1–2 cm
  - ✓ harvested by brushing or scraping machines
  - ✓ used for nutrient removal from dilute wastewaters
  - ✓ lipid content of turf scrubber algae found to be low (Mulbry et al., 2008)

Heterotrophic fermenters and algal turf scrubbers will not be discussed further because of their limitations for efficient biofuel production. The first three technology categories, the most promising for biofuels, are discussed extensively in the following sections.

3.5.5.1 Open Ponds vs. Closed PBRs for Large-Scale Microalgae Cultivation

For large-scale autotrophic algae cultivation, two main technology categories are most often considered: open high rate pond systems and closed PBRs, both of which have been studied since the early1950s (Burlew, 1953; Oswald and Gotaas, 1957). Both methods aim to supply the required resources for algal growth (light, nutrients, and carbon dioxide) in amounts as close to optimal as possible while controlling drags on production (e.g., excess dissolved oxygen, nonoptimal temperature, disease, grazing organisms). Each technology has its pros and cons for these goals; however, the foremost difference between ponds and PBRs is cost. Whereas the primary advantage of closed PBRs is their high degree of control over environmental conditions, the primary advantage of open pond systems is economy.

Thin PBRs are generally composed of clear tubes, flat plates, or bags of narrow diameter. These elements are oriented vertically or horizontally. PBRs in any configuration must maintain a continuous flow of liquid algal suspension in order to prevent sedimentation and facilitate mass transfer of carbon, oxygen, and heat. Flow is generated using mechanical pumps or airlift pumps. PBRs may be illuminated directly with sunlight or artificial light or through some form of light distribution such as mirrors or fiber optics.

A feature of thin PBRs that has multiple effects is their ability to simultaneously grow high cell concentrations at high rates of productivity. By making the vessel thin, more light is available per unit volume than would be found in a 20 to 30 cm deep pond; thus, more cells can be grown per unit volume (1 g/L to nearly 30 g/L). During mid-day, when insolation is often much greater than the cells can use, self-shading provided by the dense culture results in each cell being exposed to less than full sunlight (although this same effect is present in ponds). Also, when light is not at full intensity, self-shaded cells are likely to become adapted to low light and become more photosynthetically efficient. If cell concentration and mixing intensity are optimized, the typical cell in the PBR will be exposed to the optimal amount of light and maximize photosynthetic efficiency. Of course, the optimum changes throughout the day, so unless the PBR concentration and mixing intensity are continuously adjusted, optimum conditions are not met. Nonetheless, many researchers claim much higher productivity for PBRs (2.7 times higher in Hu et al., 1998). Others have found little difference in side-by-side tests, which is discussed in a subsequent section.

Other major advantages of high cell concentrations are decreased harvesting effort and improved volumetric reactor efficiency. The harvesting efficiency comes about primarily from needing to process less water per unit mass of algae (e.g., 3 L/g for ponds vs. 1 L/g or less for thin PBRs).

Some technical challenges for PBRs are gas exchange and fouling. Although the closed nature of PBRs prevents the outgassing of carbon dioxide (which has a cost for its injection into the medium), closed vessels tend to accumulate oxygen, which inhibits growth. Therefore, separate vessels are often used for carbon dioxide injection and stripping oxygen from the medium. These vessels can serve the dual purpose of removing oxygen while adding needed carbon dioxide, nutrients, and algal seed culture. Carbon dioxide may also need to be injected into the medium at intervals along the PBR itself. The narrow diameter and large surface area of many PBRs make any biofouling or scaling of the transparent surface

especially troublesome. Also, when PBRs become contaminated with unwanted species, cleaning and disinfection of great lengths of tubing may be problematic.

The following summarizes the advantages listed by Pulz (2001) and the disadvantages listed by Weissman et al. (1988) and Lehr and Posten (2009).

Advantages

- Culture attains higher cell densities, reducing harvesting costs.
- Contamination is greatly reduced.
- When water cooling is not used, PBRs have little evaporation.
- Land area required may be less with vertical PBRs.
- Controls important growth parameters such as pH, temperature, oxygen level, etc.
- Materials can be inexpensive.
- Thorough mixing aids mass transfer.
- Culture is protected from rain, which can wash out cultures and introduce contaminants.

Disadvantages

- Contamination may be delayed, but it is not avoided.
- Without evaporation, PBRs retain excessive heat. Evaporative cooling is often used, increasing water consumption.
- Vertically oriented PBRs may reduce needed land area but also increase hydrodynamic pressure, which greatly increases the energy required for mixing.
- Mixing energy use is high because of head loss in the thin culture vessels and the need for intensive gas exchange.
- Because of mass transfer limitations, each tubular or bag unit within a PBR system must be relatively small—no more than 100 m^2. Supplying the required amounts of even the cheapest materials for thousands of units becomes prohibitively expensive.
- Maintaining high flow rates damages algal cells and inhibits their growth, in addition to requiring large amounts of auxiliary energy.

Lehr and Posten (2009) summarized the recent innovations reported for closed PBR designs. The following lists the companies or authors described and the specific types of improvements they have made in design.

- **Reduced installation and maintenance costs**
  - ✓ V-shaped bag reactor (Novagreen)
  - ✓ Green wall panel (Rodolfi et al., 2009)
  - ✓ Annual reactor (Zittelli et al., 2006)
- **Improved mixing efficiency**
  - ✓ Inclined tubes (Merchuk et al., 2007)
  - ✓ "Triangular" air-lift reactor (Vunjak-Novakovic et al., 2005)

- ✓ 3D matrix system (Greenfuels, no longer in business)
- ✓ Flat panel airlift reactor (Subitec)

- **Reduced energetic cost**
  - ✓ G3 design (Solix)

- **Improved light distribution**
  - ✓ "Area-efficient" PBR (Zijffers et al., 2008)

None of these incremental advances are likely to change the overall prospects for proposed biofuel facilities that would use PBRs exclusively, as described in the next section. Costs will be too high. Instead, hybrid PBR and pond facilities are a better prospect.

3.5.5.2 PBR and Pond Costs

PBR costs vary widely depending on complexity and materials, from tubes mounted on moving heliostats (e.g., E.ON Hanse Company, Hamburg, Germany) to high-rate ponds in hoop greenhouses, which could also be considered closed PBRs, although ponds will have much lower cell concentrations than thin PBRs (2–5 cm). PBRs utilizing heliostats have been estimated to cost approximately $\$180/m^2$ of growth surface (Dimitrov, 2007), and high-rate ponds covered with inexpensive plastic greenhouses have been estimated to cost approximately $\$4/m^2$ for the pond plus $\$30/m^2$ for the greenhouse (Lundquist et al., 2010). These capital costs consider only the growth reactor and exclude the substantial costs for water and carbon dioxide delivery infrastructure and algae harvesting and processing. The cost per barrel of oil produced by these facilities can be roughly compared as follows: assuming an annual average 5 g/m^2/day extractable oil is produced and a 20% per year capital and operating charge for the algae production facilities, the cost of the algae oil produced would be $2800 per barrel for the heliostatic system and $530 per barrel for the covered pond. Again, these costs consider only the reactors, not a complete algae biofuel production system.

Clearly, these production costs would have to decrease to be competitive with oil in major markets. The obvious ways to decrease this cost are to (1) decrease capital or O&M costs, (2) increase productivity per unit cost, or (3) increase revenue from coproducts of the algae biofuel production. PBRs may play a role in increasing coproduct revenue and productivity, but whether these benefits can outweigh their much higher capital and O&M costs vs. ponds is a point of intense debate in the algae production field (U.S.DOE, 2009). The question is: can complete PBR systems, with total costs at least ten times higher than open ponds, increase revenue sufficiently to offset the increased cost?

With covered ponds being the lowest cost PBRs currently conceived, PBRs do not have much latitude for cost reductions. One simplifying option is to eliminate the greenhouse structure and allow the transparent plastic to float on the pond surface. However, this approach has many problems, such as poor gas exchange and light-blocking biofilm growth. In terms of O&M costs, covered ponds will not provide savings over the open ponds, since the mixing and carbon dioxide delivery operations will be similar.

In terms of the prospects for increased productivity by PBRs, the literature comparisons of areal productivity between closed PBRs and open pond systems have not been

straightforward because of the varied spacing and configurations of PBRs. One standardized, experimental comparison of closed and open systems resulted in a nearly equal areal productivity of 26 $g/m^2/d$ for both systems (Pedroni et al., 2004). Zittelli et al. (2006) introduced a standardized measure of overall areal productivity and achieved a nearly 80% increase in algal biomass productivity over values in Pedroni et al. (2004), using a closed tubular PBR. However, Zittelli et al. stated that their system is not amenable to large-scale production because of the mixing energy required. Creation of genetically modified algae with high oil productivity is currently an area of intense research, but the complexity of eukaryotic algae and the fact that cyanobacteria do not produce oil leaves many years of research ahead (Lundquist et al., 2010).

Although coproduct revenues (e.g., feeds, fine chemicals, wastewater treatment) can greatly lower the cost of the lipids produced, these coproduct markets would be saturated by substantial algae production. For a widespread algae biofuel industry, lipid production costs must be low on their own, without significant coproduct revenue.

The DOE Aquatic Species Program (1978–1996), a long-term algae biofuel research program, abandoned its use of closed PBRs and focused entirely on cultivation in open ponds shortly after the publication of a techno-economic analysis of cultivation methods by Benemann et al. (1982). At commercial scale, that practice has continued. Currently, nearly all commercial cultivation of high-value nutritional algae is conducted in open ponds. Closed PBRs currently dominate research and development in the algae biofuel field (Lehr and Posten, 2009), and both technologies will likely be needed at each future biofuel facility to achieve low-cost mass culture of specific algal strains. Each facility would require a small number of costly PBRs to produce inoculum of particular strains. This inoculum would be scaled up routinely in ponds inside greenhouses, which then would produce inoculum for full-scale open ponds. This procedure would mitigate invasive strains and might produce the lowest cost algal biomass (Weismann et al., 1988).

3.5.5.3 Water Demand

The minimum required water demand of algae production depends largely on

- The need to maintain optimal water quality through periodic blowdown (applies to both PBR and open ponds)
- Replenishment of water lost to evaporation (applies to open ponds)
- Water incorporated into the harvested algal biomass
- Water lost through leaks from the pond into the ground (this can be minimized or eliminated through proper pond design)

Because of these factors, water demands will vary widely depending on the specific application, the water quality of the make-up for growth media, the local climatic conditions, and the species of algae grown. Defining specific water demands cannot be done precisely without project-specific information, although some general information can be developed.

- **Algae biomass uptake**. Approximately 5 to 10 kg (1.3–2.6 gallons) of water is consumed per kg of algae biomass produced (Murphy and Allen, 2011).

- **Volume of growth medium**. In order to cultivate algae, a minimum amount of water is required as a medium for growth. Murphy and Allen (2011) estimate that for *Chlorella* suspensions, for every 1 gram of algae produced, "more than a kilogram of noncellular water is required" as a medium.

- **Evaporation** varies widely based on water and air temperature, ambient humidity, precipitation, and wind velocity. Wigmosta et al. (2011) have modeled evaporation from algae ponds across the entire United States and estimate that evaporation losses can vary from 4 to 21 megaliters (ML) per hectare per year (1.3 to 3.9 AF per acre per year) in the western United States, and from less than 1 to 4 ML per hectare per year (<1 to 1.3 AF per acre per year) elsewhere.

- **Blowdown** requirements to maintain optimal water quality will vary widely based on evaporation rate, species of algae grown, and quality of the water supply. Saline (high TDS) waters will require more frequent blowdown than freshwater (recycled water is generally considered a freshwater source). As water evaporates from the pond surface, the remaining water becomes more concentrated and must be replenished with supplementary water.

3.5.5.4 Water Quality Requirements

Algae have the ability to tolerate water with poor quality, including saline waters and even seawater. Specific water quality requirements or guidelines have not been established, although algae have been grown widely in wastewater treatment ponds (Lundquist et al., 2010); most recycled water supplies will be suitable for use as growth media for algae cultivation.

As technologies for algae cultivation for the purposes of biofuels production are developed, specific alga strains may be targeted for their benefits as biomass feedstocks. If specific alga strains are cultivated, each will likely have its own specific water quality requirements and optimal water quality levels for given constituents. Salinity (TDS) is a key constituent for determining the acceptability of a water supply, although other constituents should be evaluated for their effect on the type of algae to be grown.

More critical, with respect to water quality, is the resource inputs, specifically nutrients and carbon dioxide, which are necessary to maximize algae production. Nutrients, specifically nitrogen, can come directly from the water supply when using some wastewater or recycled water. Given a typical total nitrogen concentration in wastewater of 40 mg/L, approximately 660 gallons of wastewater can produce 1 kg (2.2 lbs) of dry algal biomass (Lundquist, 2010).

3.5.5.5 Microalgae Harvesting and Processing

Although the high cell concentration possible in PBRs is a distinct advantage over dilute pond cultures, cell harvesting is a major effort for both technologies. Typical microalgal cells range from about 0.5to 30 µm in size and thus are difficult to remove by sedimentation or centrifugation. Algae with one or more of the following characteristics would aid in harvesting:

- relatively large, colonial., or filamentous
- buoyant
- floc-forming

None of these characteristics has been seen reliably in high-lipid alga species. Alternatively, chemically or mechanically assisted harvesting has been used for decades at some pond-based WWTFs (e.g., Santa Rosa, Napa, Sunnyvale, and Stockton, CA). However, such interventions are likely to severely impact the cost and net energy balances of algae biofuel facilities.

Once algal cells are grown and harvested, extraction of oil will be a challenge. Species or strains with soft or absent cell walls would be beneficial for ease of oil extraction; however, these poorly defended algae are more susceptible to predation. Instead, cell disruption technologies may be required, but again, net energy balance becomes a concern when such equipment is added to a biofuel process.

The biomass processing will most likely require dewatering and drying to allow solvent extraction of TAGs. (Dry biomass is also required by typical thermochemical biomass-to-fuel processes, such as gasification.) Waste heat or solar drying would have to be used to maintain a substantially positive energy balance for the process.

Table 3.13. Methods of Harvesting and Processing Algal Biomass for Biofuel Production

Biomass Recovery	Dewatering	Drying
Settling/sedimentation	sand beds	drum dryer
Dissolved air flotation	mechanical presses	freeze dryer
Centrifugation	--	rotary dryer
Filtration	--	solar dryer
Flocculation (natural or chemical)	--	spray dryer

A variety of methods exist for accomplishing the cultivation and harvesting of microalgae, which allows for some flexibility in design of production systems depending on local conditions, availability of resources, and species being cultivated. Major methods of harvesting and processing algal biomass for biofuel production are listed in Table 3.13.

Liquid transportation fuel is a low-value commodity with enormous demand—140 billion gallons is consumed per year in the United States alone (NRC, 2009). Therefore, biofuel production is constrained by issues of scale and economy. In order to minimize costs and maximize production, biofuel production systems must use low-cost materials or omit materials where possible, co-locate component facilities, minimize energy use, recycle water and nutrients, and produce compatible coproducts. Open ponds are used for 99% of worldwide commercial microalgae production and are likely to continue to be the best technology for large-scale algae production in the near to mid-term. In addition, because of their lower operational energy requirements, ponds should have a smaller greenhouse gas footprint than PBRs.

More generally, algae biofuel production is likely to have lower net greenhouse gas emissions than current oil crops, potentially leading to greater revenue from carbon credits (see Brune et al., 2009, for the soy case). Although Clarens et al. (2010) concluded that terrestrial oil

crops were likely to have a smaller footprint than algae, their pond analysis used several flawed or unnecessarily unfavorable assumptions. Most important was the assumption of one paddle wheel mixing station per 100 m^2 of pond, when one paddle wheel per 10,000to 40,000 m^2 is the better estimate. Another was their assumed use of chemical fertilizers instead of wastewater or recycled nutrients.

3.5.5.6 Other Algae Cultivation Uses

Algae are grown as a bioproduct in pond-based wastewater processes and are generally regarded as a nuisance or waste product that must be disposed of; however, they have been explored as a feedstock for anaerobic digestion, to limited success. Wastewater high in algae content can be dewatered and put in digesters, but the algal biomass is resistant to digestion because of its recalcitrant cell material and high ammonia content, which can impede methanogen (methane-producing bacteria) reproduction. Santa Rosa, CA, has explored algae digestion with its research project that included constructed wetland channels that polish its wastewater effluent and promote algae growth. Santa Rosa and a team of researchers explored codigesting algae biomass with animal manure and found that biogas production together improved versus digesting algae and manure separately.

Opportunities for algae cultivation at wastewater plants is limited by land area, as the ponds or raceways that are used for algae need to be relatively shallow to maximize light penetration and limit the need for mixing. The potential for these types of algae cultivation projects is not limited by water supply, and recycled water (i.e., treated wastewater) by necessity is the water supply used for growth media.

3.5.6 Potential Water Demands for BMFP

In the BMFP sector, the primary potential water demands are irrigation of agricultural crops and growth media for algae, where the demand results from evaporation and periodic blowdown. Irrigation demand is a highly site- and project-specific characteristic, depending on plant type, local climate, and soil type. It is commonly stated that biomass feedstocks for energy and biofuels should be drought-tolerant species able to grow on marginal agricultural lands, so that the crop yields will still be acceptable without the need for irrigation. However, drought tolerance and low irrigation are goals, and crop yields must be shown to be sufficient to produce economically viable crops. If crops are grown on marginal land with uncertain productivity, irrigation may be a way of boosting yields.

Representative irrigation demands per gallon of corn ethanol produced were estimated by researchers at Argonne National Laboratory for three USDA regions, as shown in Table 3.14. Region 5 includes Illinois, Indiana, Iowa, Missouri, and Ohio; Region 6 includes Michigan, Minnesota, and Wisconsin; and Region 7 includes Kansas, Nebraska, North Dakota, and South Dakota. These regions account for 89% of the corn production of the United States as of 2008. Region 7 receives the least rainfall on average and therefore must supplement with irrigation, typically from groundwater supplies (Wu et al., 2009).

Soybeans are grown primarily in the same regions as corn but generally require higher irrigation per bushel than corn, depending on the exact location. According to an analysis of the average water applied per the average yield in the 2008 USDA Farm and Ranch Irrigation Survey (2008), Table 3.15 shows the estimated irrigation requirements for soybeans in the same regions as corn in Table 3.14.

Because corn is expected to continue to be the biggest feedstock source for energy and biofuels in the coming years, the most opportunities for recycled water irrigation will come from this crop. However, the incentives for recycled water use must match up correctly because currently the use of groundwater is much more preferable because of its low cost and availability. If groundwater use becomes more restricted because of overdraft or other reasons, the lack of availability may make recycled water a good option.

Stone et al. (2010) also did an evaluation of biomass feedstock crop irrigation demands, summarized in Table 3.16. These water use factors show the total water demand of the plants; most locations where these crops are grown have varying levels of rainfall during the growing season, so the actual irrigation demand would be lower, sometimes by orders of magnitude, than that shown in the table. The values are helpful to show the relative water requirements of these crops but not as valuable for estimating potential irrigation water demands across the industry.

Table 3.14. Corn Ethanol Irrigation Demand Factors

USDA Region	Irrigation Consumed in Corn Farming (gal/gal ethanol)
Region 5 – Illinois, Indiana, Iowa, Missouri, Ohio	7.0
Region 6 – Michigan, Minnesota, Wisconsin	13.8
Region 7 – Kansas, Nebraska, North Dakota, South Dakota	321

Table 3.15. Soybean Irrigation Demand Factors

USDA Region	Irrigation Consumed in Soybean Farming (gal/gal ethanol)
Region 5 – Illinois, Indiana, Iowa, Missouri, Ohio	156
Region 6 – Michigan, Minnesota, Wisconsin	72
Region 7 – Kansas, Nebraska, North Dakota, South Dakota	1781

Table 3.16. Water Use Factors for Various Biomass Feedstock Crops

Crop	Water Requirements (gallons water/ton)	Biofuel Conversion (gallons fuel/ton crop)	Water Use Factor (gallons water/ gallons fuel)
Ethanol			
Nebraska corn	152,000	98	1551
Corn stover	152,000	78	1946
Corn stover plus grain	152,000	176	864
Switchgrass	126,000	81	1565
Grain sorghum	640,000	86	7459
Sweet sorghum	41,900	57	734
Biodiesel			
Soybean	436,000	51	8617
Canola	431,000	100	4332
Safflower (California)	543,048	75.5	7197

Source: Stone et al., 2010; NRC, 2008; Kafka, 1999; Munier et al., 2011
Note: Water use factor=all water requirements for plant growth and does not distinguish between rainfall-fed plant demands and irrigation. Water use factors for each crop are larger than potential irrigation demands.

For algae cultivation, water is used as the growth media. Water is lost by evaporation (in open systems) and must be discharged (blowdown) to maintain proper water chemistry to maximize algal growth. The water demands can vary widely for algae cultivation depending on the technology used (open ponds vs. PBRs) and the location. Evaporation varies according to local climatic conditions. Rapid algal biomass growth also requires large amounts of water to maintain proper balance of media to biomass ratios. One of the great potential benefits of algae as a biomass feedstock is that they can be cultivated in areas unsuitable for agriculture, such as deserts, and with low quality waters (e.g., high TDS) that would normally be unsuitable for irrigation. No commercialized methods of algae cultivation for biofuels production have yet been developed, so accurate estimates of water demand are speculative at this point. Current publicly available estimates of production cost of biofuels per unit volume produced from algae suggest that great technological improvements must be made before any of the potential processes could be commercialized.

It is premature at this stage to make definitive estimates of water use, and demands must be determined on a project-by-project basis. However, according to estimates by DOE's Energy Efficiency and Renewable Energy Group (EERE), evaporative losses in desert areas can be as high as 5300 gallons per day (6 AF/acre) for a 1-acre open pond system, which is a much higher rate of consumption/loss than typical irrigation agricultural operations. Blowdown losses depend on the water quality of the make-up water and the acceptable limits of the algae species being cultivated. EERE has listed water management as an area of research that needs continued study, and more conclusive estimates are not expected until the processes for cultivating algae for biomass feedstocks become commercialized.

3.5.7 Water Quality Requirements

Recycled water irrigation has been practiced widely for turf/landscape and crop irrigation. General guidelines for the required water quality of recycled water for irrigation are shown in Table 3.17. This table is intended only as a guide, as water quality requirements will vary for each crop and depend on soil characteristics.

Salt tolerance of a particular crop is typically the primary concern when selecting recycled water as the irrigation water source for agricultural crops. As the salinity of irrigation water (as measured in EC_w) increases, crop yield decreases. Selecting recycled water for agricultural irrigation requires that the grower understand the level of crop yield decrease and determine what decrease is economically acceptable. Table 3.18 lists the qualitative salt tolerance of a selection of crops used for biofuels production.

The U.S. Environmental Protection Agency (U.S. EPA) and U.S. Agency for International Development (USAID) developed "Guidelines for Water Reuse," a document that summarizes water quality considerations for agricultural irrigation projects utilizing recycled water. Those recommendations are shown in Table 3.19.

Table 3.17. Recycled Water Irrigation Water Quality Guidelines

Potential Irrigation Problem	Units	No Restrictions	Slight to Moderate Restrictions on Use	Severe Restrictions on Use
EC_w	dS/m	<0.7	0.7–3.0	>3.0
TDS	mg/L	<450	450–2000	>2000
SAR	unitless	and EC_w		
0–3		<0.7	0.7–0.2	<0.2
3–6		<1.2	1.2–0.3	<0.3
6–12		<1.9	1.9–0.5	<0.5
12–20		<2.9	2.9–1.3	<1.3
20–40		<5	5.0–2.9	<2.9
Sodium[1, 2]				
surface irrigation	SAR	<3	3–9	>9
spray irrigation with foliage contact	mg/L	<70	>70	--
Chloride				
surface irrigation	mg/L	<140	140–350	>350
spray irrigation with foliage contact	mg/L	<100	>100	
Boron	mg/L	<0.7	0.7–3.0	>3.0
Nitrogen (total N)[3]	mg/L	<5	5–30	>30
Bicarbonate (overhead sprinkling only)	mg/L	<90	90–500	>500
pH	unitless	Normal Range 6.5–8.4		
Residual chlorine (overhead sprinkling only)	mg/L	<1.0	1.0–5.0	>5.0

Source: University of California Committee of Consultants, 1974
Notes: 1= Most tree crops and woody ornamentals are sensitive to sodium and chloride; use the values shown in this table. Most annual crops are not as sensitive. 2=With overhead sprinkler irrigation and low humidity (<30%), sodium and chloride greater than 70 or 100 mg/L, respectively, have resulted in excessive leaf adsorption and crop damage to sensitive crops. 3=Total nitrogen should include nitrate-nitrogen, ammonia-nitrogen, and organic nitrogen. Although forms of nitrogen in wastewater vary, the plant responds to the total nitrogen. EC=electrical conductivity; SAR=sodium adsorption rate; TDS=total dissolved solids

Table 3.18. Relative Salt Tolerance of Agricultural Crops[1]

Common Name	Latin Name	Associated Biofuel	Threshold EC_e[2]	T[3]	MT[3]	MS[3]	S[3]
Corn (maize)	*Zea mays*	ethanol	1.7			X	
Jojoba	*Simmondsia chinensis*	biodiesel	NA	X			
Safflower	*Carthamus tinctorius*	biodiesel	6.7	X			
Soybean	*Glycine max*	biodiesel	5.0		X		
Sugar beet	*Beta vulgaris*	ethanol	7.0	X			
Sugarcane	*Saccharum officinarum*	ethanol	1.7			X	

Source: Westcot and Ayers, 1985; Bassil and Kafka, 2002
Notes: 1=These data serve only as a guideline to the relative tolerances among crops. Absolute tolerances vary with climate, soil conditions, and cultural practices. EC_e=soil electrical conductivity; MS=moderately sensitive; MT=moderately tolerant; NA=not available; S=sensitive. Sensitivity refers to the relative drop in crop yield as salt concentration (TDS) increases. T=tolerant

Irrigation systems, in particular large-scale systems with large capital investment, should be designed or modified to be compatible with recycled water. Typical considerations for design of an irrigation system utilizing recycled water as adapted from Pescod (1992) are as follows:

- **High salinity** (e.g., TDS). Select salt tolerant crops and account for the need to flush soils to minimize build-up of salts.
- **High cation concentration** (e.g., calcium, magnesium, sodium). Assess potential for sodicity hazards and potential augmentation of soil with gypsum.
- **High metal or other toxic ion/element concentrations**. Assess uptake of these constituents by the crops and potential risk if used as biomass feedstock.
- **High nutrients**. Minimize leaching of excess nutrients (especially nitrate) to underlying groundwater.
- **High suspended solids**. Add screening or filters to prevent buildup or clogging in irrigation system with suspended solids.

Table 3.19. U.S. EPA and USAID Agricultural Irrigation Guidelines for Recycled Water

Constituent	Long-Term Use (mg/l)	Short-Term Use (mg/l)	Remarks
Aluminum	5	20	Can cause nonproductiveness in acid soils, but soils at pH 5.5 to 8.0 will precipitate the ion and eliminate toxicity.
Arsenic	0.1	2	Toxicity to plants varies widely, ranging from 12 mg/L for Sudan grass to less than 0.05 mg/L for rice.
Beryllium	0.1	0.5	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Boron	0.75	2	Essential to plant growth, with optimum yields for many obtained at a few tenths of a mg/L in nutrient solutions. Toxic to many sensitive plants (e.g., citrus) at 1 mg/L. Usually sufficient quantities in reclaimed water to correct soil deficiencies. Most grasses are relatively tolerant at 2.0 to 10 mg/L.
Cadmium	0.01	0.05	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in nutrient solution. Conservative limits recommended.
Chromium	0.1	1	Not generally recognized as an essential growth element. Conservative limits recommended because of a lack of knowledge on toxicity to plants.
Cobalt	0.05	5	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper	0.2	5	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solution.
Fluoride	1	15	Inactivated by neutral and alkaline soils.
Iron	5	20	Not toxic to plants in aerated soils but can contribute to soil acidification and loss of essential phosphorus and molybdenum.
Lead	5	10	Can inhibit plant cell growth at very high concentrations.
Lithium	2.5	2.5	Tolerated by most crops at concentrations as high as 5 mg/L; mobile in soil. Toxic to citrus at low doses; recommended limit is 0.075 mg/L.
Manganese	0.2	10	Toxic to a number of crops at a few tenths to a few mg/L in acidic soils.
Molybdenum	0.01	0.05	Nontoxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high levels of available molybdenum.
Nickel	0.2	2	Toxic to a number of plants at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH.
Selenium	0.02	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low levels of selenium.
Tin, titanium, and tungsten	-	-	Effectively excluded by plants; specific tolerance levels unknown
Vanadium	0.1	1	Toxic to many plants at relatively low concentrations.
Zinc	2	10	Toxic to many plants at varying concentrations; reduced toxicity at increased pH (6 or higher) and in fine-textured or organic soils.

Constituent	Recomm. Limit	Remarks
pH	6	Most effects of pH on plant growth are indirect (e.g., pH effects on heavy metal toxicity described previously).
TDS	500–2000 mg/l	Below 500 mg/L, no detrimental effects are usually noticed. Between 500 and 1000 mg/L, TDS in irrigation water can affect sensitive plants. At 1000 to 2000 mg/L, TDS levels can affect many crops, and careful management practices should be followed. Concentrations greater than 2000 mg/L can be used regularly only for tolerant plants on permeable soils.
Free chlorine residual	<1 mg/l	Concentrations greater than 5 mg/l cause severe damage to most plants. Some sensitive plants may be damaged at levels as low as 0.05 mg/l.

Source: U.S. EPA and USAID, 2004

3.5.8 Potential for Recycled Water Use

The greatest potential opportunities for recycled water use in the BMFP sector are irrigation of crops and growth media for algae. In particular, irrigation of feedstock crops that have an established market in biofuels production, such as corn and soybeans, has the greatest near-term potential in areas with limited water resources. Corn and soybeans are both grown primarily in areas that receive plentiful rainfall during the growing season or have extensive groundwater available. For recycled water to be advantageous to corn and soybean growers, a combination of factors must be present, including no other water supply available in large quantities and recycled water available at a relatively cheap price to compete with other low-cost irrigation water supply sources. The most likely scenario is a wastewater agency that has a discharge limitation and is looking to dispose of treated effluent via a method other than discharge to surface water.

The potential for recycled water demands for irrigation will vary widely according to the location of the project. These variations can include differences in average annual demand based on the local climatic conditions, but they can also include wide variations in demand year to year. For example, in California's Mediterranean climate, summer months consistently have limited to no rainfall, so if the crop's growing season is in the summer, irrigation demands will be fairly consistent each year. In areas where crops rely partially on rainfall during the growing season, irrigation demands can vary year to year if rainfall is limited or the timing of rainfall does not correspond to critical times in the plant's growing cycle. If the project is driven by a need to dispose of treated wastewater, this yearly variation can require that the recycled water supplier find contingencies for disposal.

With great potential there is also great uncertainty, as, other than corn and soybeans, other potential biomass feedstock crops have not found an extensive market yet because of the not-yet-established demand for these feedstocks in the biofuels industry. Because of this uncertainty, as well as the great variation of irrigation and water demands for algae based on the local site conditions, this study does not include estimates of the potential for recycled water on an industry level. Most of the crops that can be used to make biofuels can be grown for food, so the opportunities for recycled water use for irrigation may begin there, if there is a need. Table 3.20 illustrates the estimated relative level of opportunity for recycled water use for potential demands in the BMFP sector. The potential quantity of demand for BMFP production is high relative to other typical recycled water uses (irrigation is the highest category of water demand in the country overall), but the uncertainty and specific requirements for each project will limit the extent of implementation.

Table 3.20. Opportunities for Recycled Water Use in BMFP

Water Reuse Opportunity	Relative Quantity of Demand Opportunity	Likelihood of Implementation	Time Frame
Corn irrigation	high	medium	near term (ongoing)
Soybean irrigation	high	medium	near term (ongoing)
Oilseed irrigation	potentially high	medium	mid- to long term
Cellulosic crop irrigation	near term—low long term—high	uncertain	mid- to long term
Algae cultivation	near term—low long term—high	uncertain	mid- to long term

Chapter 4

Issues and Barriers

The availability of recycled water is only one aspect of fully realizing its potential in the energy and biofuels industries. Other aspects can determine the feasibility and desirability of recycled water use in the four energy sectors when a theoretical demand exists. To promote expansion of recycled water in the four energy sectors, these other aspects must be examined, and strategies must be developed to properly address them. The purpose of this section is to

- Compile potential issues and barriers for implementing recycled water projects in four energy sectors.
- Provide potential strategies for managing these issues and barriers in order to better promote recycled water use.
- Identify areas where more work or research is necessary to advance the state of recycled water use in the energy sectors.

There are six general categories of issues and barriers that may complicate the use of recycled water in the four energy sectors:

1. Cost and supply availability considerations
2. Outreach to potential users
3. Market uncertainty
4. Regulatory issues
5. Institutional issues and arrangements
6. Public acceptance, support, and outreach

These categories represent the nontechnical considerations that will contribute to the decision to use recycled water. In some cases, these considerations are bigger drivers or impediments to recycled water use than technical aspects of supplying recycled water. This section discusses each issue and describes how it affects the selection of recycled water use and how these issues can be addressed in order to better promote recycled water use in the four energy sectors.

4.1 Cost and Supply Availability Considerations

For energy and biofuel projects, water supply is typically a secondary, though critical, aspect in the planning process. Water is a prerequisite for most energy and biofuels projects, and cost is a primary consideration when selecting a source. More and more frequently, water supplies are becoming a critical factor in project implementation in the four energy sectors as supplies become scarce, even in non-arid regions of the country. Concurrently, water agencies are implementing gradually higher levels of treatment and seeking additional supplies of high-quality water to meet rising demand. Higher levels of treatment requires more capital investment and higher cost of water as a result. New supply sources are also generally more expensive than the current sources because they also require significant capital investment. Desalination, demineralization, expansion of surface water reservoirs,

groundwater aquifer storage and recovery, and other potable water replacements require new facilities and, in some cases, much higher energy use and operating costs than previous sources.

In comparison, recycled water becomes more attractive as the price for other sources rises. Recycled water costs are not increasing at the same rate as potable water supplies because, on the whole, the supply of the recycled water input (e.g., treated wastewater) still greatly exceeds the demand. There are exceptions to this generality in service areas that have been highly proactive about maximizing recycled water use, but across the country vastly more wastewater is being discharged than is being put to beneficial reuse. As recycled water becomes more widely used and recognized as a viable replacement for other water supplies, the demand and therefore price will also increase. However, given that the vast majority of wastewater supplies are not utilized, the time scale for price increases is long.

To make the decision to select recycled water as a supply source for projects in energy and biofuels, a series of steps must be undertaken, including

1. **Technical alternatives analysis**. Determine the water quantity and quality needed. Identify project facilities needed, including treatment processes and conveyance facilities. This step includes preliminary capital and O&M cost estimates for project alternatives.
2. **Project cost analysis**. This step is done from the perspective of both sides of the project, the potential user and the supplier. The cost analysis is used to determine whether the project is feasible through examination of direct financial costs as well as indirect project benefits and costs.
3. **Determination of rates**. This step is ultimately determined by the recycled water supplier but not without collaboration and negotiation with major users to determine viable rates. Rates can come in various forms, including service cost recovery versus incentive-based rates, and tiered, uniform, or seasonal rates.

The issue of cost is a key driver in determining the suitability of recycled water for any project, and both sides—user and supplier—have different motivating factors and priorities in selecting a water source. Collaboration is critical in developing a recycled water supply project that meets the needs of both sides and minimizes cost.

4.1.1 Technical Alternatives Analysis

The technical alternatives analysis is dependent on project-specific conditions, including whether a wastewater agency or municipality already owns and operates a tertiary (or higher) treatment plant and whether it has an existing pipeline distribution system for conveying recycled water. This analysis will include examination of the following items:

- Treatment alternatives. Determine the need for new or expanded treatment facilities based on the water quality and quantity needed to meet demands.
- Conveyance alternatives. Determine the need for new pipelines, pump stations, and related appurtenances that would be required to connect new users.

A cost estimate needs to be developed for each alternative so that they can be compared and analyzed. The cost estimates should include the following:

- Capital
  - ✓ conveyance; includes pipelines, pump stations, and appurtenances
  - ✓ treatment; typically includes tertiary and disinfection processes and advanced treatment, if necessary
- O&M
  - ✓ electric power
  - ✓ chemicals
  - ✓ replacement of equipment and consumables
  - ✓ labor

Cost curves from readily available documentation and firm experience were incorporated into features of the Decision Support Tool developed as part of this study so that users can do a screening-level cost estimate for proposed projects. The tool is discussed in detail in Chapter 5.

4.1.2 Project Cost Analysis

After defining project alternatives and estimating their cost, the next step is to analyze the benefits and costs of each alternative and compare these to other water supply options. As described in WateReuse Research Foundation (2006), project costs can be evaluated through two methods: (1) a financial analysis, which is based solely on cash flows of direct project expenses and revenues; or (2) an economic analysis, which analyzes issues of cost and benefit more broadly and tries to quantify both direct and indirect costs and benefits that do not necessarily have financial impact on the immediate project stakeholders.

For projects in the four energy sectors, the recycled water supplier and the user will view the importance of various costs differently. Both sides must collaborate during the cost analysis phase to plan a successful project that is mutually beneficial and built for success in the long term.

4.1.2.1 Recycled Water Supplier Cost Considerations

On the supply side, some form of benefit–cost economic analysis is typically preferred to determine both direct, financial factors and indirect, nonfinancial factors that may provide value and incentive to implement a project. One common method of benefit–cost analysis is known as the Triple Bottom Line analysis, which quantifies financial, social, and environmental costs and benefits to produce an overall project life cycle cost. Recycled water utilities are generally publicly owned and therefore have a duty to provide multiple benefits beyond low cost. Also, many recycled water projects are funded by other public entities at the state and federal level, and these funding sources typically require that the benefits of the project stretch beyond financial payback on project costs. Therefore, a more comprehensive cost analysis is preferred in many cases to show the project has benefits beyond simply low cost to the user and revenue for the agency. The supplier will likely be interested in using recycled water for more than one user and type of use, and the benefit–cost or life cycle analysis performed prior to the project will include considerations for capacity, level of treatment, and effluent quality that meet all user needs.

4.1.2.2 Recycled Water User Cost Considerations

In most cases for potential recycled water users in the four energy sectors, direct financial costs typically outweigh any considerations regarding indirect project benefits and costs. The power, biofuels, and agricultural industries are highly competitive, low profit margin businesses, and efforts to minimize cost are essential to maintaining profitability. Keeping resource costs down, including water supply, is essential; however, there are factors that have monetary values that must be calculated based on the value to the user. Some examples are

- **Supply availability.** If no other water sources are available, recycled water can be the only option.
- **Reliability.** Recycled water is more reliable than surface water supplies that can be reduced during drought years. Also, recycled water supply availability is not expected to change drastically as a result of climate change, although surface water supplies might.
- **Expected future cost.** The current cost of various water supplies may favor one over another, but if the future costs of those same waters are taken into consideration the evaluation may reverse. Factors that can contribute to an escalating future cost for potable water supplies include climate change impacts to water resources; increasing scarcity and therefore higher market value; and tighter regulations that require additional treatment. These factors are further discussed in Section 4.1.4.
- **Water quality consistency**. Both recycled water and surface water supplies can have seasonal water quality variations, resulting in complications and increased chemical use for conditioning at the user site.

4.1.3 Determination of Rates

Accounting for costs, including O&M and the debt service on financing, will allow for a determination of an estimated rate needed to recover them. In many cases, the cost for a recycled water project cannot always be strictly offset with rate revenue while still making recycled water an attractive alternative to other sources. Typically, recycled water is priced at some fraction of the cost of other sources of water, or only operating expenses are recovered by rates. Many potable water supplies are not priced to cover the full marginal cost of new users, so setting recycled water rates relative to underpriced potable water rates results in further mismatch between costs and revenue. If the cost of recycled water is still not economical for the project being investigated, even after setting it low relative to potable water, the burden will fall to the prospective user to either find another water supply source or identify how to finance the recycled water project to bring down the cost of water.

The actual rate by the user will ultimately depend on a combination of factors beyond the facility capital and O&M cost. The technical analysis for a project will consider different types and configurations of facilities that produce and convey the needed water for a project. Within that analysis, the cost of different alternative configurations will be compared. Options such as the level of treatment preferred by the user can be influenced by the ultimate cost to that user. Treatment can be configured to provide the lowest cost alternative while still meeting technical requirements.

Suppliers ultimately decide on what rate will be charged but develop these rates with consideration toward their users. There are two general categories of rates, based on either recovering the capital and O&M costs or maximizing recycled water use (i.e., market based). In many cases, the rate needed to recover the capital, O&M, and financing costs of a project result in a value higher than that of other alternative sources, making recycled water financially less advantageous. Therefore, in most cases there must be incentives for using recycled water. These incentives can include

- **Low rates relative to other water supplies.** Commonly, recycled water suppliers set rates at a percentage of potable water rates for a given location (80% of potable water rates is common). Grant funding, if available, can also offset the capital cost of these projects and reduce the rate charged to the user. In other cases, rates are set to cover recycled water system operating costs alone and not to recover capital costs. Incentivized rate structures are common in which recycled water suppliers receive major nonfinancial benefits to offset potable water demands. For example, in Southern California, wholesale potable supplies are unreliable year to year, and deliveries from outside the area require large energy inputs and incur high energy costs.
- **Drought reliability.** Recycled water has the benefit of not being affected by climatic variations (e.g., drought) from year to year. Users do not have to worry about a drop in water allocations if drought conditions occur and can plan water supplies reliably.
- **Lack of available water supply alternatives.** In some areas, water resources have been fully allocated or are not available in sufficient quantities to meet a project's demands. The example referenced previously is the Tharaldson Ethanol plant near Fargo, ND. No water supplies were available, so the plant was compelled to use recycled water from the Fargo treatment plant. Even areas without arid climates may find this an increasingly common dilemma as time goes on.
- **Targeted rates.** If a specific group of users is benefiting from a recycled water project—for example, an expansion of the distribution system or expanded treatment to enhance water quality—those users specifically benefitting from the improvement may be required to pay higher fees. Existing users that benefit from recycled water quality and delivery in its current form could avoid the degree of rate increase that the targeted users would pay. Another method of targeting rates is based on user type; for example, industrial users pay one rate, and irrigation users pay another.

The rate paid by the user will involve negotiations with the supplier, and will consider the following factors:

- Are there other supplies available in sufficient quantities?
- Are there incentives to use recycled water?
- What is the reliability of the other supply options?
- Who will own and operate the completed facilities?
- Who else benefits from the project? Are all users paying equally into the system?

A selection of typical rates from recycled water suppliers in various locations across the United States is shown in Table 4.1.

Table 4.1. Sample Recycled Water Rates

City/Agency	Industrial Customers ($/AF)	Irrigation Customers ($/AF)
San Jose (CA)	527	510
Irvine Ranch Water District (CA)	322	475
Santa Rosa (CA)	1535	1470
Delta Diablo Sanitation District (CA)	260	260
El Paso Water Utilities (TX)	405	405
Tampa (FL)	523	523
Phoenix-Area Sub-Regional Operating Group (SROG) agreement with Palo Verde Nuclear Station (AZ)	$53 (near term) $300 (ultimate)	N/A

Sources: San Jose, 2011; Irvine Ranch Water District, 2012; Santa Rosa, 2012; Delta Diablo Sanitation District, 2011; El Paso Water Utilities, 2011; Arizona Public Service, 2010
Note: DDSD's monthly charge includes an additional fixed monthly charge specific for each user and not shown here.

4.1.4 Other Cost-Related Issues

Beyond just the project cost analysis and rates, there are cost-related issues that may not be immediately apparent.

4.1.4.1 Expected Future Cost of Water

A project owner needs relative assurance of the future cost of water. A low current cost is important, but that low cost must also be assured for a period of time or must escalate at a known rate in order to plan operations and project profitability at an industrial facility. There are several factors that are expected to contribute to an increase in cost for potable water supplies, which will have less of an effect on recycled water.

- Climate change impacts to water resources. Climate change is expected to greatly influence the water resources of most of the country, causing changes such as more rainfall in some areas and less in others, or less snow and more rain high in the watersheds that flow into water supply reservoirs. These changes will challenge water managers and are expected to result in more water scarcity.
- Increasing water scarcity. Population growth comes with higher demands for limited potable water supplies. Rates and availability now may suggest an advantage over recycled water, but that may be lost when accounting for future rate increases due to increasing market value and scarcity.
- Tighter regulations that require additional treatment. New treatment processes may be required to meet regulations for constituents that do not yet have enforceable limits but will in the future. Existing supplies will likely come at a higher cost because of increasing treatment.
- Increased cost of new water supplies. New sources of water, such as desalination and demineralization of groundwater, or augmentation of existing supplies, such as expanded reservoir storage, will have marginal costs much higher than current

supplies, so the overall water portfolio cost will steadily increase. Recycled water is likely less expensive than most of these new supplies, depending on project details.

The future cost of recycled water may be expected to increase as well for agencies where the recycled water system is more fully developed and demands are approaching supplies, especially in high-demand periods like the dry season.

High-quality water supplies will be more sought after and reserved for drinking water (highest beneficial use) or environmental uses. As recycled water increases in acceptability to be used in indirect or even direct potable reuse applications, it will be considered more valuable, and prices will reflect that. The Groundwater Replenishment System of Orange County Water District is an example of a large-scale, indirect, potable water reuse project. As these types of projects become more prevalent, the recycled water supply will become indistinguishable from high-quality raw water supplies from a cost standpoint because the use of recycled water is not limited to "lower quality" uses.

4.1.4.2 Irrigation Water Cost Issues

Large-scale agricultural irrigation is a special case. Typically, the cost of water for agricultural irrigation is very low, sometimes an order of magnitude or more lower than typical potable water costs. There can be a few reasons for this. One is that the irrigator uses on-site groundwater, for which the marginal cost is equal to the power cost of the groundwater pump. Another is that the irrigator has water rights for surface water diversions that enable it to pay below-market rates to meet its full demands. Irrigators must balance the cost of water with the revenue gained from yield increases due to irrigation. For low-value commodity crops, such as all biomass feedstock crops, water costs must be minimized, or the growers will not be able to compete in the marketplace. Use of recycled water at typical rates (on the order of $200–$1000 or more per AF) is not likely to be competitive with other irrigation water sources.

One way to keep recycled water costs low and competitive for agricultural irrigation is to limit the level of treatment to as low as is acceptable to the irrigators; for example, by using secondary treated wastewater rather than tertiary. If water quality is acceptable, the project avoids the cost of the additional treatment step, and the rate could be based only on the conveyance. This scenario is ideal for an application such as cultivation of algae for biomass. Secondary effluent can have benefits over tertiary in that algae can thrive in the secondary effluent because of the typically high nutrient content and can be used as a final polishing step in the treatment process to reduce nutrients and other constituents prior to discharge.

Another instance in which recycled water costs can be kept low, even with tertiary treated water, is if suppliers set their rates artificially low in order to use recycled water deliveries as a point of discharge. These recycled water suppliers would likely have discharge restrictions during irrigation months and be compelled to find an alternative way to dispose of their effluent. In these instances, a properly located irrigation user may be able to receive recycled water at low or no cost for mutual benefit.

Last, one way to both mitigate the cost of recycled water and maintain proper water quality is to blend recycled water with another supply source. The Salinas Valley Reclamation Project and Castroville Seawater Intrusion Project combine to provide recycled water and Salinas River water to growers in the Salinas Valley region in California. Recycled water is used to augment the river and groundwater in order to minimize seawater intrusion into the

groundwater basin. The blended water is used to irrigate high-value vegetable and fruit crops (e.g., artichokes, strawberries, and broccoli).

A separate issue specifically related to agricultural irrigation is that irrigation water demands are concentrated within a few months during the growing season, from spring through the end of summer or early fall. This concentration of demand is common in recycled water projects, as most users of recycled water are irrigation users in arid areas where rainfall is concentrated in a winter wet season. If recycled water is selected as a supply source, and there is sufficient supply to meet irrigation demands during these dry months, there is no impact to cost. However, often the irrigation demand exceeds the supply of recycled water available during the summer months, so to fully irrigate with recycled water, seasonal storage must be installed. Seasonal storage ponds are typically built with earthen levees and can have a capacity of many millions of gallons in order to provide the needed reserve water from wet months for later use. The cost of seasonal storage can render the project much less cost effective, but in some instances it is worth the additional cost.

4.2 Outreach to Potential Users

One issue that is certainly limiting more widespread use of recycled water by industrial and agricultural users in general and would apply similarly to users in the four energy sectors is outreach to potential users. Agencies and cities that have been most successful in expanding recycled water use within their service areas have been proactive in reaching out to potential users to sell the benefits of recycled water as an alternative to other supplies. The participating agencies on this project have had a range of experiences with adding new users, but all have found that contacting potential users to discuss the benefits of recycled water helps to increase demand for the service.

Historically, recycled water programs start when the need for service to a large-demand user arises, such as the Geysers project, the Calpine power plants (LMEC and DEC), or the Lodi Energy Center. Once established, recycled water use is maximized through building a large base of support. Santa Rosa has continuously reached out to agricultural users in the service area, and as Russian River water becomes more limited for such uses as frost control, the city has promoted the use of recycled water as a replacement, to great success.

DDSD holds periodic discussions with existing power plants and other industrial customers in its service area and most importantly keeps them involved in the approval process of new power plants. DDSD is fortunate to have a large base of potential industrial users and new power plants but recognizes that the users do not come to the suppliers unless there is an outside driver. In California, the CEC promotes the use of recycled water for use in new power plants if at all possible based on site- and project-specific conditions.

Lodi worked with NCPA as it went through the approval process for an expanded Lodi Energy Center on a site next to the city's treatment plant. Fairfield–Suisun Sewer District has kept closely involved with Fairfield as it has promoted the construction of a new power plant on land immediately adjacent to the Fairfield–Suisun Sanitary District treatment plant site.

Recycled water suppliers across the country can follow similar patterns, exploring options for new users in the four energy sectors to maximize recycled water use and increase revenue, rather than discharge wastewater. The best strategy for targeting users in these industries is to monitor the project approval process, whether through the state power commissioning agency, environmental documentation process, or area planning commissions. The

participating agencies of this study suggest submitting official comments through these processes as a way to show support for the project and a willingness to participate and contribute to its success.

One suggested reason for the need for outreach, specifically to industrial users, is that water is simply a secondary concern to most of them. If the status quo works, whether relatively high cost potable water or low-quality raw water, industrial users are reluctant to try new options. However, the benefits of recycled water, reduced rates, better quality, better reliability, or others, can be unknown to them. Outreach can be the push needed to help a project gain momentum.

4.3 Market Uncertainty

The industries within the four energy sectors include many that have not yet become commercialized, and within the industries there are many competing technologies and processes in development and still much uncertainty as to which technologies will come out ahead in the commercialization process. These conditions present both an opportunity and great uncertainty in that there may be huge markets for new recycled water projects as new facilities are built, but these projects may be short lived if the technologies do not pan out in the marketplace. The issues related to market uncertainty are concentrated in the BFPP, BEPP, and BMFP sectors, although some industries with PHP are included here as well, notably CSP power plants.

4.3.1 Commercialization of Biofuels

Ethanol from corn is still a growing sector, and there is much less risk involved in investing in the supporting resources and infrastructure that are required for the industry to thrive. Conventional biodiesel is much the same in terms of risk, although the potential for growth is limited. The growth of corn ethanol is likely to continue in the near term as other biofuels are developed because, although ethanol is well established and corn ethanol is widely used across the country, policy makers and investors have recognized the need to identify ways of producing biofuels that do not compete directly with food sources, referenced previously as advanced biofuels.

These advanced biofuels represent a potentially significant opportunity for recycled water, as they will likely require large quantities of cooling and process water. However, recent history in these industries shows that although the technologies have been proven on pilot and demonstration scales, there is still much work to be done to commercialize the technologies and produce quantities of biofuels large enough to impact the market. Because there are so many start-up companies in this area, many are aiming for lofty schedule and production targets. To meet those targets, they are focusing on the items in their operations that will show they have a viable technology for producing commercial-scale quantities of biofuels, and these items do not always include water as a top priority. Instead, facilities are looking to prove viability, with cost cutting and process efficiencies coming later.

4.3.2 Dedicated Energy Crop Feedstocks

Established crops, such as soy and corn, do not have much risk associated with their use as biomass feedstocks, and the main concern is price. Other commonly available feedstocks can be fairly simple to investigate on a trial basis and seem to be the focus of a lot of recent activity in the biofuels industry because of their wide availability and low cost, in particular

MSW. However, dedicated energy crops—those for which a large market does not currently exist but that have great potential biofuel productivity characteristics—have significant uncertainty and risk. First, growers have little experience with these crops and are generally risk averse. Researchers have been exploring the option of dedicated energy crops such as switchgrass and camelina, among others, but without a significant market to fall back on if the biofuels industry does not come through, dedicated energy crops are not yet an attractive option to most growers.

In addition, although researchers and others have identified potential dedicated energy crops, such as camelina, switchgrass, and jatropha (for biodiesel), the success of these crops at large-scale production levels must still be demonstrated. Jatropha, although not an ideal crop for the United States (it grows better in tropical climates), represents a prime example in which the theoretical benefits (e.g., high oil yield, drought tolerance, can grow on marginal lands) have not yet translated to real-world performance. Although the jatropha tree can tolerate droughts, its yield drops without sufficient water. Large-scale projects in India and the Philippines produced disappointing yields and were unable to meet crop delivery agreements based on yield projections. Although not directly applicable to the United States, as jatropha is not recognized as a suitable crop here, it represents the risk in putting significant resources into an unproven crop.

4.4 Regulatory Issues

The regulatory environment can have an effect on the viability of recycled water projects. Often, the regulatory process will favor recycled water projects over more conventional water development sources, such as surface water or groundwater. For example, CEC has promoted the use of recycled water during the new power plant approval process. Permitting and regulatory benefits may be short lived (they may be tied to current permits that expire) or viewed as an ongoing benefit that can be considered in cost sharing and financing.

Whether a state currently has an existing regulatory structure for recycled water may help or hinder the use of recycled water. In states where recycled water is widely used, such as California, Florida, Texas, and Nevada, a structured set of regulations and permitting processes have been developed and used so that the regulatory process will typically be more involved, but the outcome and cost of the process are predictable and fairly certain. As it relates to the four energy sectors and industrial users of recycled water in general, the regulatory process for recycled water is simplified because of its limited exposure to the public.

Where recycled water is uncommon, or in areas with limited implementation, regulations either do not exist or are not fully developed. This may result in a simplified and accelerated regulatory process, but projects will have to be addressed on a case-by-case basis. Without a regulatory framework, the project proponent is advised to develop a permitting approach in cooperation with the designated regulator for wastewater discharge (U.S. EPA or state delegated agency) and patterned after a simplified approach that has been proven in another state or region that the applicable regulator can use to bolster the approval process. Specific regulatory issues include

- state-level recycled water regulations
- water rights
- worker safety/public health

- environmental permitting
- discharge

Using other sources may require studies showing no impact to the environment or water rights of others. As compared to other water supply alternatives, recycled water projects may avoid costly and time-intensive studies and evaluations demonstrating that the water supply can be developed and used without creating environmental impacts or water rights implications on downstream users or water rights holders. This avoidance of cost and time delays may justify some level of incentive or financial participation by other project beneficiaries.

4.4.1 State-Level Recycled Water Regulations

The bulk of recycled water use has been concentrated in California, Florida, Arizona, and Texas, and these states offer the longest history of established regulatory regimes concerning recycled water. A list of explicitly allowable recycled water uses are shown for these states in Figures 4.1 through 4.4.

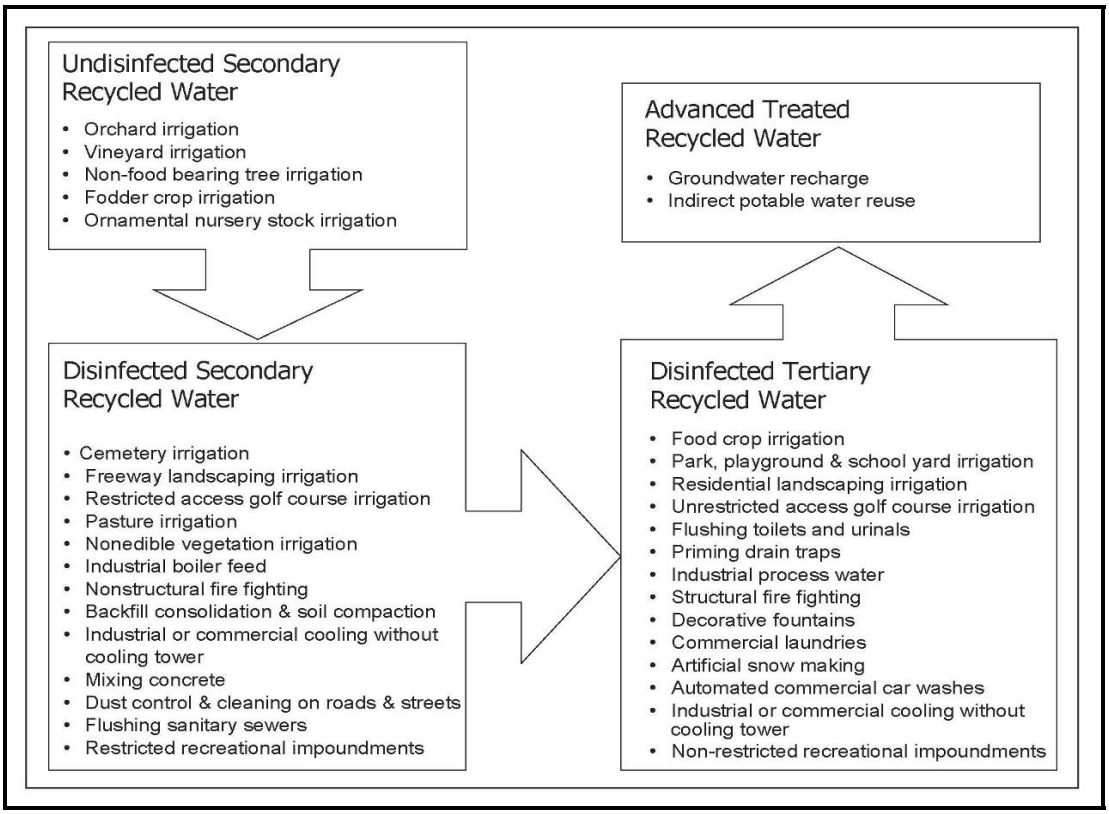

Figure 4.1. Allowable recycled water uses under Title 22 in California.

Source: California Code of Regulations, 2001. In some cases, groundwater recharge with disinfected tertiary water is allowed.

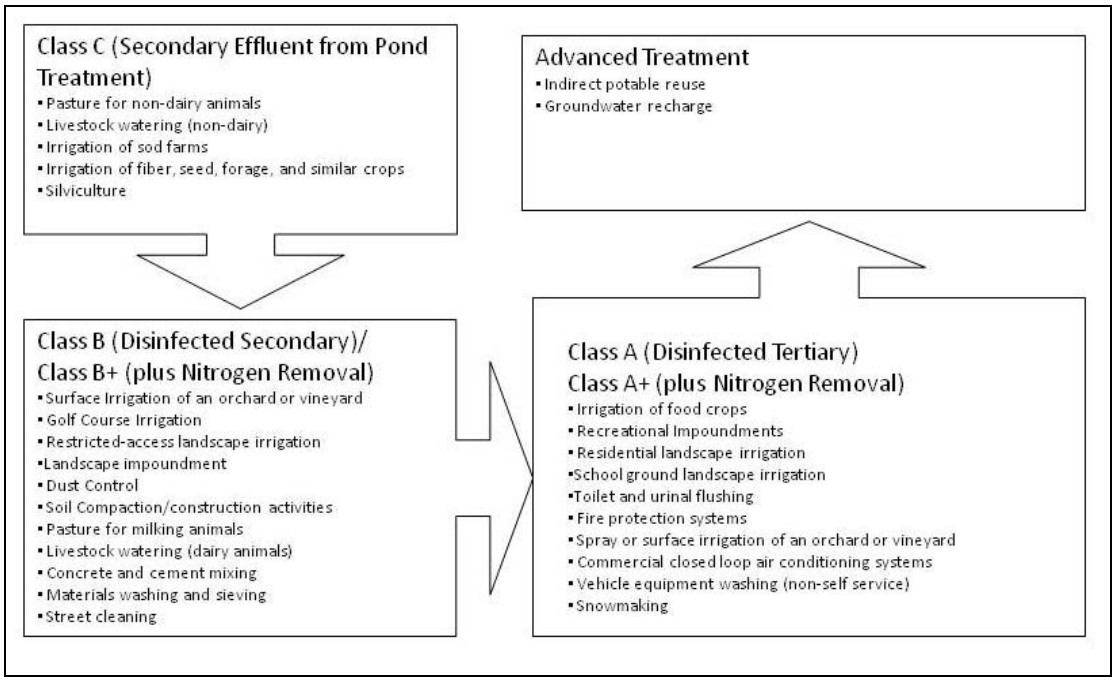

Figure 4.2. Allowable recycled water uses under Chapter 11, Article 3, for Arizona.

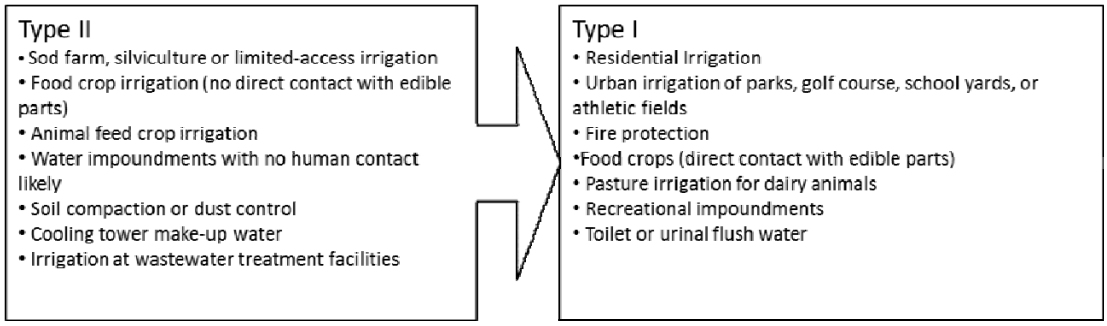

Figure 4.3. Allowable recycled water uses under Rule 210.32 for Texas.

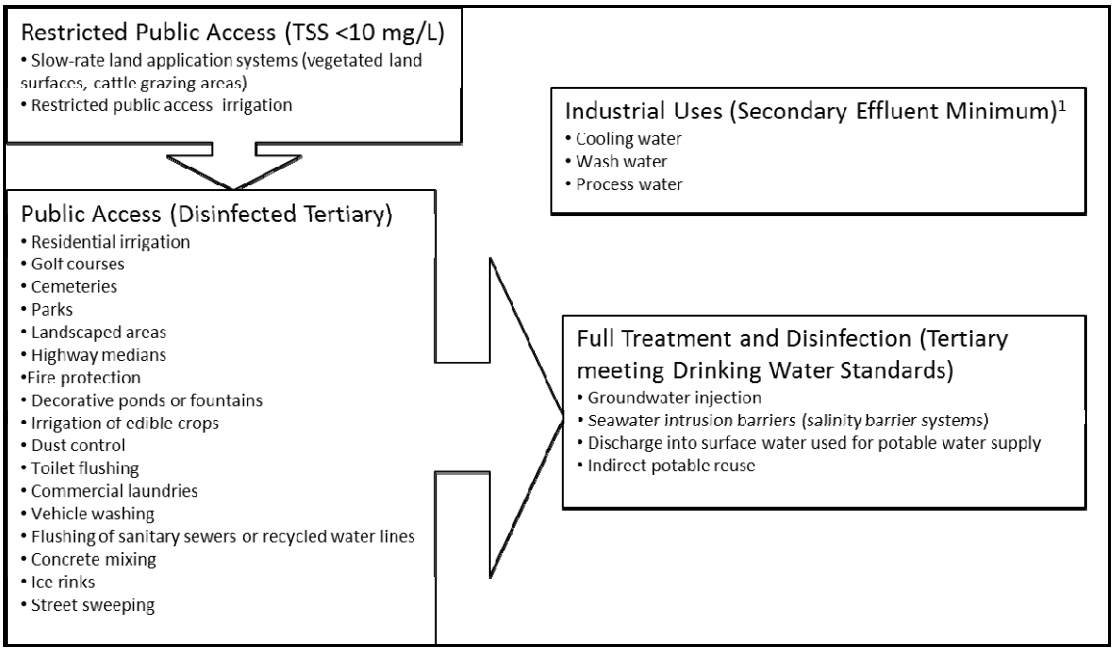

Figure 4.4. Allowable recycled water uses under Rule 210.32 for Florida.

Notes: Florida allows industrial users to set their own water quality requirements based on process need, with a minimum of secondary effluent as the starting point.

In states and regions where recycled water is widely used, a structured set of regulations and permitting processes have been developed and used so that the regulatory process will typically be more involved, but the outcome and cost of the process are predictable. Currently, 28 states have regulations regarding recycled water; 9 states have regulations specific for industrial applications; and 15 have guidelines for water reuse. Minnesota does not have established recycled water regulations but uses California's Title 22 recycled water regulations as a guide to approve projects on a case-by-case basis (Craddock Consulting Engineers, 2006).

As it relates to the four energy sectors, the regulatory process for recycled water is simplified because of the limited exposure of the recycled water product to the public. Specifically, in California, the major issue to date for energy-related projects using recycled water has been for heat and power projects where cooling tower drift has generated PM10 in the vicinity of sensitive receptors. Typically, in places where recycled water is uncommon or in the early stages of implementation, regulations are nonexistent or not fully developed. This lack of a regulatory framework may result in a simplified and accelerated regulatory process, but each regulator will approach new conditions with a different perspective, so these types of projects will have to be addressed on a case-by-case basis. Without a regulatory framework, the project proponent is advised to develop a permitting approach in cooperation with the designated regulator for wastewater discharge (U.S. EPA or state-delegated agency) and patterned after a simplified approach that has been proven in another state or region that the applicable regulator can use to bolster the approval process..

Regulations are going to typically favor recycled water in most applications in the four energy sectors as compared to other water sources unless the regulators perceive the project as an unreasonable or wasteful use of water. Other specific regulations that affect the use of recycled water are described in the following sections.

4.4.2 Water Rights

The area of water rights needs to be examined early in the project feasibility stage to ensure that there are no fatal flaws in changing the point of discharge of the treated wastewater prior to its becoming recycled water and being used for the project in question. The issue of water rights is one that has arisen specifically in California for two reasons: (1) the downstream water rights holders and water managers who may be managing salinity and other water quality parameters may not be supportive of a reduction in the freshwater-treated wastewater discharge that would otherwise positively affect freshwater availability and salinity in their jurisdiction; and (2) the process for clarifying the water rights issues related to wastewater discharges is not clear cut, so review of water rights petitions for change can be long, with unclear outcomes. Water rights issues should not prevent the recycled water project, but they can delay it while the petition process is completed. Water rights can be a constraint for those dischargers who have rights holders downstream of their discharge point (e.g., Stockton, CA, and Las Vegas, NV). In such cases, the issue that detracts from the benefit of using recycled water is that the project will have to account for the loss of downstream potable water availability due to decreased discharge to the body of water.

4.4.3 Environmental Documentation and Permitting

Recycled water projects, like any other infrastructure project, may require environmental documentation under the National Environmental Policy Act if the project is within a federal jurisdiction or receiving federal funds or similar state-level environmental law, such as the California Environmental Quality Act. Generally, for any project, the objective under these laws is to limit impact to the surrounding human and natural environment, so the strategy for most projects is to plan facilities that are within previously disturbed (i.e., developed) areas and avoid potential threatened or endangered species habitats and locations that may have sensitive cultural resources. Although most projects within the four energy sectors will be located squarely within areas that have been previously disturbed, such as industrial areas and agricultural lands, some projects will likely encounter environmentally sensitive areas; for example, CSP projects in the desert or projects with pipelines that pass through rural or remote areas.

Projects with linear facilities (pipelines, power lines, roads) and processing plants will require permits for stream crossings, dredging/filling activities, and other resource-related impacts. No unusual barriers or impacts for recycled water projects for the bioenergy sector are anticipated that are not present for other such projects. For recycled water projects such as biomass production, in which the water is used for irrigation or in ponds with a potential discharge to groundwater or surface water, the potential impacts of such discharges need to be evaluated. In most cases, the impacts will be equal to or less than those associated with the current treated wastewater discharge. In California, where the issues of incidental runoff of recycled water and antidegradation of groundwater associated with irrigation of recycled water were creating roadblocks to recycled water project implementation, the SWRCB developed a Statewide Recycled Water Policy (SWRCB, 2009) in order to clarify and streamline the process for developing and permitting recycled water projects to the benefit of the state. A cornerstone of the policy, which was jointly developed by water industry professionals and representatives of nongovernmental organizations concerned about the impact of treated wastewater and recycled water on the environment, is the establishment (by 2016) of salt and nutrient management plans for the groundwater basins in California. This process should allow for an aggregated and efficient approach to the protection of groundwater in the state and permitting of recycled water projects, with a focus of resources

on the basins where the groundwater is beneficially used and most likely to be impacted by current and anticipated irrigation and other practices.

4.4.4 Discharge

Recycled water suppliers may promote partnerships to reduce their discharges, either to address individual permitting requirements or as a result of a collective effort to reduce discharge mass loading, such as a total maximum daily load program. In such cases, the recycled water project costs may be subsidized or partially financed by the regional discharge partnership, or that partnership or agency may be able to secure financing or outside funding where clear project benefits can be demonstrated. An example of such a partnership is the North Bay Water Reuse Authority (NBWRA) in Marin, Sonoma, and Napa counties, CA, where recycled water, which would otherwise be discharged by several agencies to a sensitive, shallow estuarine environment, is being used to offset potable water and decrease discharges to the bay (NBWRA, 2011).

If the recycled water project involves a discharge of excess water, blowdown, or concentrate from the process of treating the recycled water (e.g., in a cooling tower), the discharge of that water will need to be addressed. To the extent that the discharge water is produced on or near the wastewater plant, and that plant can process the stream efficiently without impacting its ability to meet its discharge permit limitations, there will be a minor potential barrier to overcome for the recycled water project, which may simply involve a cost transfer between entities, such as an industrial waste charge or high strength surcharge if the wastewater agency has such a program. If the discharge stream needs to be discharged directly to a receiving water or downstream of the entire treatment plant, the discharger will be required to evaluate the impacts of the discharge on the current permit holder and potentially on the receiving water. Depending on the magnitude and strength of the discharge stream relative to the current discharge by the wastewater treatment agency, this can be a substantial barrier to a bioenergy project. In the case of power plant siting projects in California using recycled water for heat and power, the evaluations have involved toxicity testing of the discharge to ensure permit compliance, pilot testing of post-treatment processing for heavy metals removal, and other such resource- and time-intensive evaluations. Where constituents of concern (salts, metals) are concentrated in the bioenergy project, an alternative that can be considered is ZLD, which is energy and cost intensive but reduces the regulatory barrier substantially.

4.5 Institutional Issues and Arrangements

For arrangements in which an industrial facility partners with a recycled water supplier to receive recycled water, the primary institutional agreement that must be put in place is the water purchase agreement. Users and suppliers must formally agree to many aspects of a recycled water program in order to ensure that that program meets the needs of both, designate responsibilities between the parties, and prepare both sides for circumstances beyond normal operations.

Agreements can include other aspects depending on the specific case. The goal of these agreements is to maintain a successful working relationship between user and supplier so that the needs of both are met. A recycled water supplier is unique compared with other potential water suppliers in that it is also likely to be the entity responsible for discharges from the industrial facility in question for blowdown and other waste flows. Requirements and arrangements are generally similar in all four energy sectors, although some issues vary in importance; some facilities cannot tolerate loss of water supply and therefore require high

reliability from the supplier (such as baseload power plants), whereas others, like irrigators, can tolerate some level of service interruption.

4.5.1 Recycled Water Service Agreements

The recycled water service agreement, also potentially called a water purchase agreement, is the center of the relationship between a potential user from one of the four energy sectors and the supplier. Generally, when an industrial facility selects a source of water and water is integral to running the facility, the facility will enter into a binding agreement to ensure that the source of water meets its requirements for quantity, reliability, quality, and cost, among other related needs. If recycled water is the selected source, the agreement is generally in line with agreements from other sources, with some key differences. The main items covered by a water purchase agreement for recycled water supply are listed here.

4.5.1.1 Quantity

How much water will the facility or operation need? The water purchase agreement typically sets a quantity that the recycled water supplier must be capable of meeting, according to the specified requirements in the agreement. Provisions may include variability according to seasons or daily fluctuations. A prioritization system may also be included to ensure that a user is guaranteed a certain supply, even when supply limitations exist and other users draw from the same distribution system. For irrigators, agreements can be set up to meet some minimum level of demand independent of seasonal demand variations. For agricultural irrigation of commodity crops where fallowing is an option, it may be feasible to agree that the user take no water in water-short years when the supplier needs to allocate supply to others who need higher supply reliability and can pay more.

4.5.1.2 Quality

The recycled water supplier must guarantee that it can meet the water quality specifications agreed to in the water purchase agreement. These requirements will include constituent limits for the recycled water supply and are likely to also include constituent limits on blowdown or other discharge return flows to the recycled water (i.e., wastewater treatment) facility. Many times, the onset of a recycled water project supplying a large industrial customer will come with improved treatment processes. The water purchase agreement will include the agreed-to performance requirements of the new treatment process.

4.5.1.3 Reliability

For industrial facilities in particular, reliability is a high priority. Baseload electricity generators need to ensure their production will not be interrupted by loss of water supply. Other facilities, such as biofuel production plants, ensure profitability based in part on maximizing online time, and interruption of water service could cause the facility to lose revenue. Irrigators have more leeway regarding the need for uninterruptible supply. Irrigation demand can vary year to year, and daily requirements can be relaxed under most circumstances, so irrigators can withstand a period of reduced or no water deliveries, although the water purchase agreement would likely limit these periods to specified requirements agreed to by both sides. Reliability aspects that should be considered as part of the agreement include (1) coordination of planned maintenance to parallel facility down time at both sites, (2) provision for operational flexibility to allow for unexpected emergencies, and (3) planning for construction of new or replacement facilities and coordination of

construction. Many times, these aspects are overlooked during the initial creation of the agreement and must be coordinated as conditions arise.

4.5.1.4 Rates

The water purchase agreement naturally includes the agreed-upon rate that the user will pay to the supplier. The rate can include provisions for increases over time or may be set at a flat amount for the duration of the agreement. Other aspects of rates included in the water purchase agreement could include whether the rates are "tiered" so that the cost of additional gallons of recycled water increases above certain set limits.

4.5.1.5 Ownership and Responsibilities

As part of the negotiations for a water purchase agreement and for a recycled water supply project in general, the two sides will decide who will own which facilities that are required components of the system. The two sides must also determine who is responsible for O&M of the component facilities. For example, DDSD operates its RWF to serve water to the nearby power plants, LMEC and DEC, but the RWF facility capital costs were financed by Calpine, the owner of the two power plants. Under their agreement, DDSD staff is responsible for O&M at the plant site, and a recycled water coordinator at the power plant sites is responsible for meeting recycled water regulations related to worker safety, air quality, and discharge issues. The inclusion of responsibilities is critical to ensure continuous service and avoid conflicts that may arise during emergency situations.

In addition, the use of recycled water often includes more reporting requirements to regulatory agencies, including monitoring data, recycled water usage data, and development of procedures to meet requirements for working with recycled water. The recycled water supplier is typically responsible for initial training of staff at the use site to introduce them to the regulatory requirements of using recycled water and for maintaining communication between the two sides to ensure procedures are meeting the requirements.

4.5.1.6 Term of Agreement

Both sides would benefit from a stable, long-term relationship to avoid uncertainties. Recycled water purchase agreements tend to have terms spanning decades in order to assure the user of a supply and the supplier of a consistent customer, so they can plan future expansion of their recycled water system.

4.5.1.7 Provisions for Nonperformance

Both sides should also consider provisions for nonperformance according to the requirements in a water purchase agreement. It is likely that potential industrial recycled water users will face significant impacts if, under avoidable circumstances, a recycled water supplier fails to meet its obligations under the agreement. Including provisions for nonperformance, monetary penalties, or indemnification will provide incentive to maintain service as required by the agreement. Generally, the consequences for nonperformance by the user (e.g., suspension of water demands) are less severe to the recycled water supplier than vice versa; however, both sides should consider these consequences so that impacts and uncertainty are limited for the unlikely circumstances that would lead to nonperformance.

4.5.1.8 Discharge Arrangements

Industrial users of recycled water have to dispose of the unconsumed (blowdown) portion of their water demand, whether through return flows back to the recycled water/wastewater treatment plant, discharge via their own outfall, or disposal via a combination of ZLD and trucked solid waste. Irrigators tend not to have return flows, although they do have to account for drainage. Discharge must be accounted for in the water purchase agreement when the unconsumed portion of flow is returned to the recycled water/wastewater treatment plant. Depending on exactly where the return flow is discharged, the wastewater plant will have its own water quality requirements that need to be met in order to not disrupt treatment processes and ensure the wastewater treatment plant's discharge limitations are not exceeded. For this reason, it is typical that water quality limitations are set on the return flow coming from the recycled water user for such constituents as TDS, ammonia, and heavy metals.

4.5.2 Strategies for Successful Agreements

The water purchase agreement is tied closely to the design of the recycled water treatment and delivery system. A supplier cannot guarantee certain levels of quantity and quality without the proper treatment and conveyance facilities, so it is crucial that the two sides discuss the aspects that will eventually be included in the water purchase agreement early on during the planning stages to ensure all needs are accounted for. If the facilities are already largely in place, the early discussions will hinge on whether the existing treatment, conveyance, and storage facilities can meet requirements of the potential new user or whether new facilities will need to be designed and constructed. The major considerations in design that affect the water purchase agreement are described in the following sections.

4.5.2.1 Treatment Process Selection

The potential recycled water user should determine minimum water quality requirements early on in order to select treatment processes that are capable of meeting those requirements or determine if existing treatment processes are capable of meeting the requirements in their current state. The requirements in the agreement must be based on real world capabilities, so it is best to have collaboration between the two sides if the current facilities do not meet those requirements.

4.5.2.2 Level of Redundancy

Redundancy is critical for maintaining reliability and uninterrupted service while still allowing for regular maintenance and unexpected repairs. The degree of reliability (e.g., 100% online factor) should be decided early in the planning of a recycled water project so that redundancy can be designed into the facilities or added to an existing facility. Redundancy encompasses additional stand-by equipment such as pumps, treatment processes or even power supply and also includes provision of backup water supplies for emergency situations when recycled water simply cannot be provided.

4.5.2.3 Monitoring

To maintain uninterrupted service and ensure that facilities are operating properly, monitoring of flows, water quality, and facility operations is critical. Industrial facilities and recycled water treatment plants typically have supervisory control and data acquisition systems, which can be used in conjunction with instrumentation to monitor a system in real time, so the key decision is to select the correct instrumentation and locations to monitor essential data. For example, if TDS is a limiting factor for the number of cycles of concentration in a cooling tower, an inline probe measuring electrical conductivity will allow the facility to alert the recycled water treatment plant when it will need to increase demand as TDS increases.

4.6 Public Acceptance and Outreach

Public outreach is a critical aspect of all recycled water projects; without public buy-in, many recycled water projects fail. This aspect is just as true for energy and biofuel applications as for other types of recycled water projects, but the lack of direct public exposure and awareness of these water uses for industrial facilities and nonfood crop irrigation limits the urgency that arises in cases where the public comes into direct contact with use areas, such as park irrigation and dual plumbing. There are a few specific issues related to recycled water use in the four energy sectors that bear consideration of public outreach.

Responding to stakeholders' concerns about recycled water is important in any recycled water project, and it is always wise to be proactive as the project is initiated. There are few cases where power plants or other industrial facility projects were halted because of public outcry specifically over the use of recycled water as the facility's water supply source. In fact, in many cases the public specifically encourages the use of alternative, so-called degraded supplies over high-quality supplies used for potable demands. However, it is always prudent to engage local stakeholders beyond those directly involved in the project, such as community civic groups, local environmental organizations, or neighborhood associations. For industrial cooling applications, there may be concern over drift of recycled water from the cooling towers, although these concerns can be allayed by technology (drift eliminators), which may be required by air quality regulators anyway, and by informing stakeholders about the many successful applications that use recycled water.

For irrigation, concerns about contamination will likely not arise since irrigators in the BMFP sector will not be producing food crops. One strategy to assure no possible exposure to recycled water is by limiting access to fields or posting typical recycled water signs.

Beyond the concern over direct exposure to recycled water in irrigation, a rising concern for biomass feedstock production is that of nonfood crops replacing land previously used to grow food. This displacement can be a concern to the public because: (1) it may cause an increase in the price of food crops, which has already been experienced in corn markets to some degree; and (2) clearing land to add to the aggregate amount of agricultural land to produce biomass can result in adverse environmental effects, such as less carbon sequestered in plant tissue (e.g., trees cut down to grow energy crops). There is no proven strategy to address these concerns, which are only emerging now. However, the recycled water supplier should not be seen as promoting one use of irrigation water over another but rather as simply maximizing the use of recycled water.

Typical strategies for reaching out to the public and stakeholder groups are through public meetings during the planning process of a proposed expansion of a recycled water system, one-on-one meetings with specific groups, and outreach media such as Websites, advertisements, and other promotional materials.

Chapter 5

Decision Support Tool Overview

This section describes the objective of the tool and its interface format. The types of data utilized in the tool, how different types of users (recycled water suppliers vs. potential users) will use the tool to access these data, and what useful information users will be able to gather from the tool to help guide their decision-making process on whether to use recycled water (or serve new users) are also described. The tool is available at the following link: http://reuse-energy-biofuels.rmcwater.com

5.1 Tool Objective

The objective of the tool is to provide guidance for both recycled water suppliers and potential users in the four energy sectors. The intent is to provide a planning-level screening tool to provide both quantitative and qualitative guidance to the user as to whether recycled water will work in the user's particular situation. The guidance provided will include suggestions for the most likely level of treatment, conveyance facilities, potential demands, water quality requirements, and other project considerations, including location, which may influence the decision to use recycled water.

The tool is also a way to introduce the world of water reuse to industries covered under the four energy sectors in order to identify opportunities for water reuse in such industries. It will guide users who do not have a specific project in mind toward potential sources of recycled water (if the tool user is a potential recycled water user) or toward potential demands (if the tool user is a recycled water supplier). For a recycled water supplier, the tool will provide an introduction to the four energy sectors, including their potential water demands and what water quality requirements such demands have. For potential users in the four energy sectors, the tool will introduce considerations of using recycled water, including water quality and treatment levels, and direct them to potential recycled water sources.

One goal for the tool is to make it as useful as possible to the largest number of potential users. Part of achieving this goal is to make the interface user friendly and engaging while also providing useful outputs that can be applied to real-world scenarios. The tool includes a map browser feature that allows the user to interact with the areas around the facility or service area and see what kind of users or recycled water sources are nearby.

5.2 Tool Format

The tool is Web based to take advantage of the readily available mapping application programming interface from Google Maps. The project team originally began development of an Excel-based tool, but given the level of analysis for this project and the type of data available (industrywide data, with some facility-specific information), this was thought to be less useful and user-friendly. For this project, a Web-based tool with geographical features is preferable for the following reasons:

1. **Engagement**. A Web-based tool with a pleasing graphical user interface (GUI) will draw users in and encourage repeat use. The intent is to have as many users try the tool as

possible, and a key to that will be ease of use. Also, having Google Maps as the geographical tool means that most of the interface design is ready to use.

2. **Accessibility**. Making the tool accessible through the Internet means that a user can access it any time without an electronic file or program. Also, a potential user does not need to go through the process of obtaining the tool but can begin using it almost immediately. This allows a user to test it out before committing to it. More users are likely to take a test drive if the tool is easily accessible.

3. **Enhanced geographical analysis**. Many of the data available for this project have a geographical element: locations of recycled water treatment plants, biofuel processing plants, power plants, and agricultural areas; regional issues related to climate, water resources, and suitability for certain industries; and state-specific regulations. This type of data is difficult to illustrate quickly and in an interesting way without a mapping system. Integrating an Excel-based tool with a geographical information system software component is possible but would require the user to have the right software. A Web-based tool using Google Maps can display the geographical data and also contribute to calculations and analysis (for example, lengths of pipe or areas available for certain biofuel crops).

4. **Data collection**. A Web-based tool can provide an opportunity for the WateReuse Research Foundation to collect data from the users. What kind of users are utilizing the tool? What types of facilities do they represent? What types of demands, quantities, and water quality requirements do they have? A Web-based tool can provide data for further analysis to enhance and bring together the worlds of water reuse and emerging energy industries.

The following sections describe in more detail how particular users will engage the tool—what kind of data they will input, what the GUI will look like, and what kind of outputs they will receive following analysis.

5.3 Recycled Water Suppliers

The tool will serve to educate recycled water suppliers on the potential opportunities for water reuse in the four energy sectors and future opportunities that may arise as these emerging industries mature. For some sectors—in particular, BFPP, BEPP, and BMFP—large-scale recycled water demands may not materialize until these industries are fully commercialized and full-scale facilities are constructed. However, opportunities are abundant in the PHP sector, as large-scale thermoelectric power plants typically have high water demands, and some have already been utilizing recycled water for decades. The supplier can prepare by using the tool to

- Select water demands that can be met by the supplier's recycled water, given the available supply and typical water quality
- Learn what the typical water quality requirements for users in each energy sector are and the reliability and operational requirements as well
- Display locations of select potential users, including power plants, biofuel production facilities, and bioenergy facilities

5.4 Potential Recycled Water Users

The purpose of the tool for potential recycled water users is to expose them to the option of recycled water and the issues involved and help them to determine whether a recycled water source is worth pursuing for their facility. The user will be able to

- Identify potential recycled water suppliers near the facility's location, with estimates of potential recycled water capacity and, in some cases, supply availability
- Input water quality requirements to compare typical or expected recycled water quality
- Learn the applicable regulatory framework for recycled water use in the facility's location
- Identify the level of treatment needed to get the water quality required
- Receive guidance on the need for public outreach and successful strategies from similar projects

5.5 Tool Flow Chart

The flow chart in Figure 5.1 illustrates the flow of the tool.

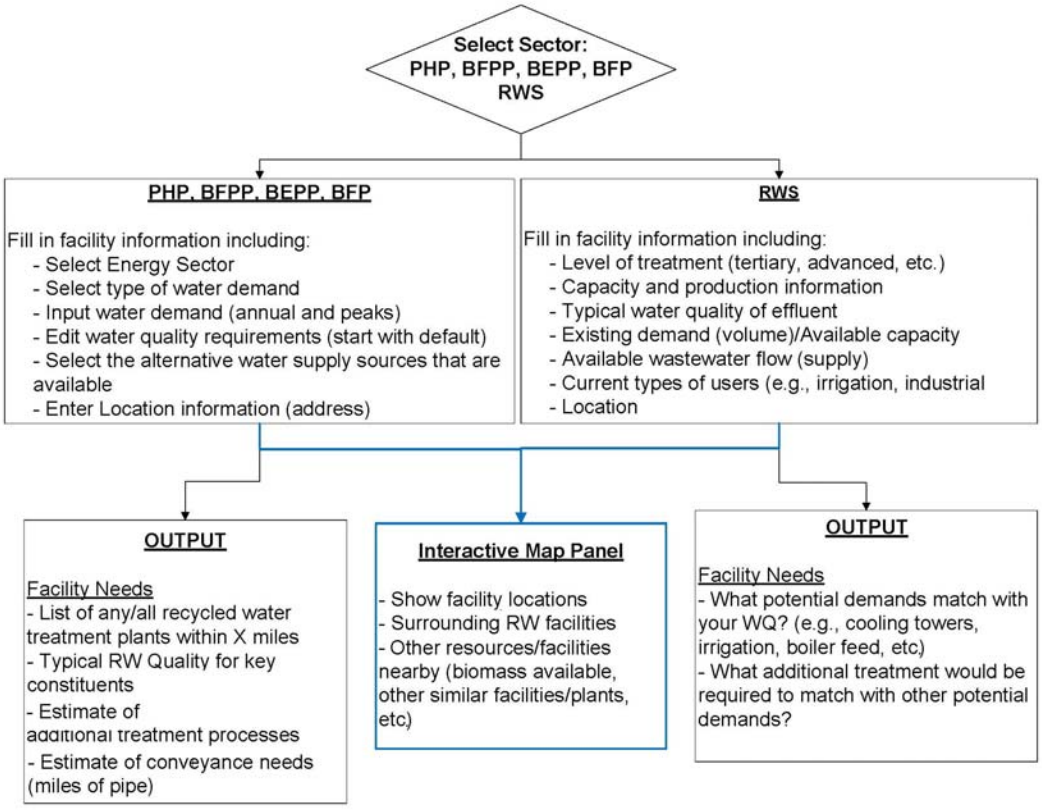

Figure 5.1. Decision support tool flow chart.

5.6 Tool Modules

The tool consists of several component modules that collect data, perform analysis, and allow browsing of the geographical data. The main components include (1) user data entry forms, (2) initial recommendations, (3) interactive map screen, and (4) screening-level project cost modules.

5.6.1 User Data Entry Forms

The core of the tool is the data that are provided by the tool users. Whether the tool user is from one of the four energy sectors or a recycled water supplier, the information entered into the forms will guide the user to recommendations, demand estimates, potential projects, and screening-level cost estimates.

The data entered into the tool will also be a resource for the WateReuse Research Foundation, as all the data will be saved to the tool database, increasing the valuable information in the interactive map screen as more people use the tool. Example user data entry forms are included on Figures 5.2 through 5.8.

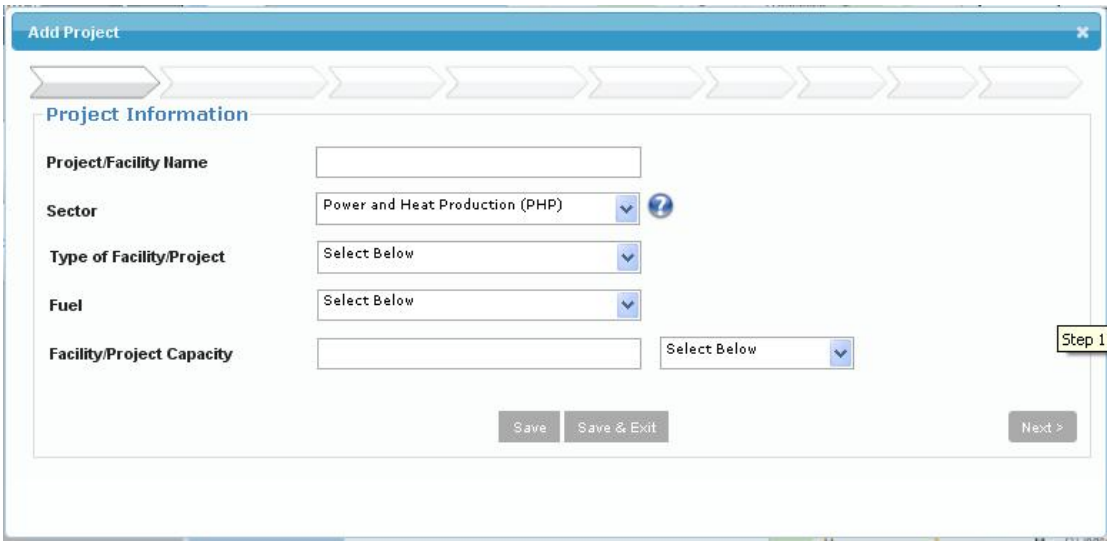

Figure 5.2. Example interface, user input panel, general information.

Figure 5.3. Example interface, user input panel, location screen.

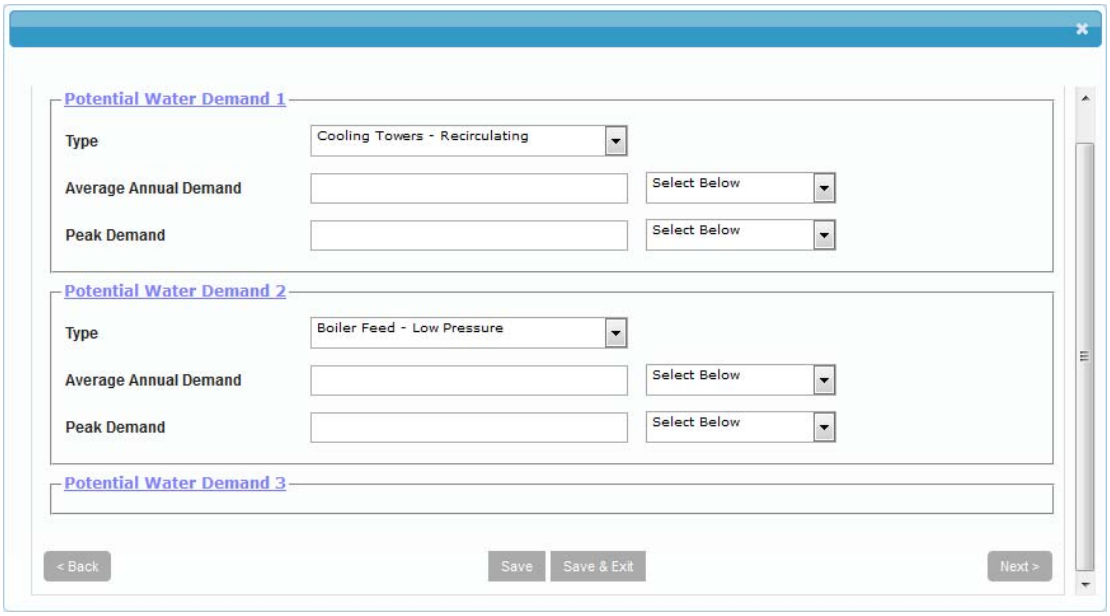

Figure 5.4. Example interface, user input panel, water demands screen.

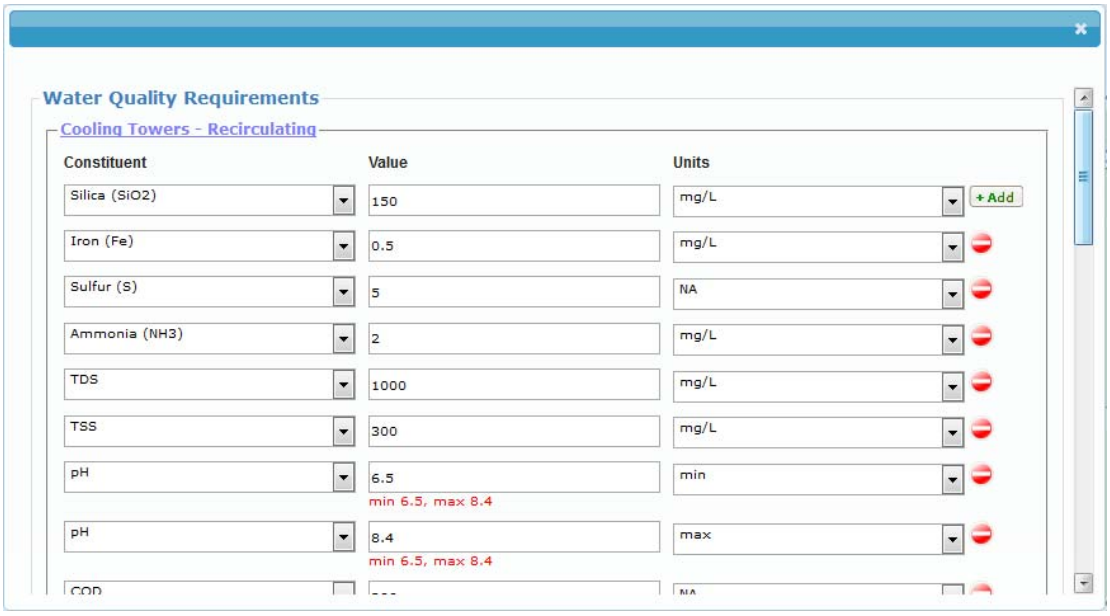

Figure 5.5. Example interface, user input panel, water quality requirements screen.

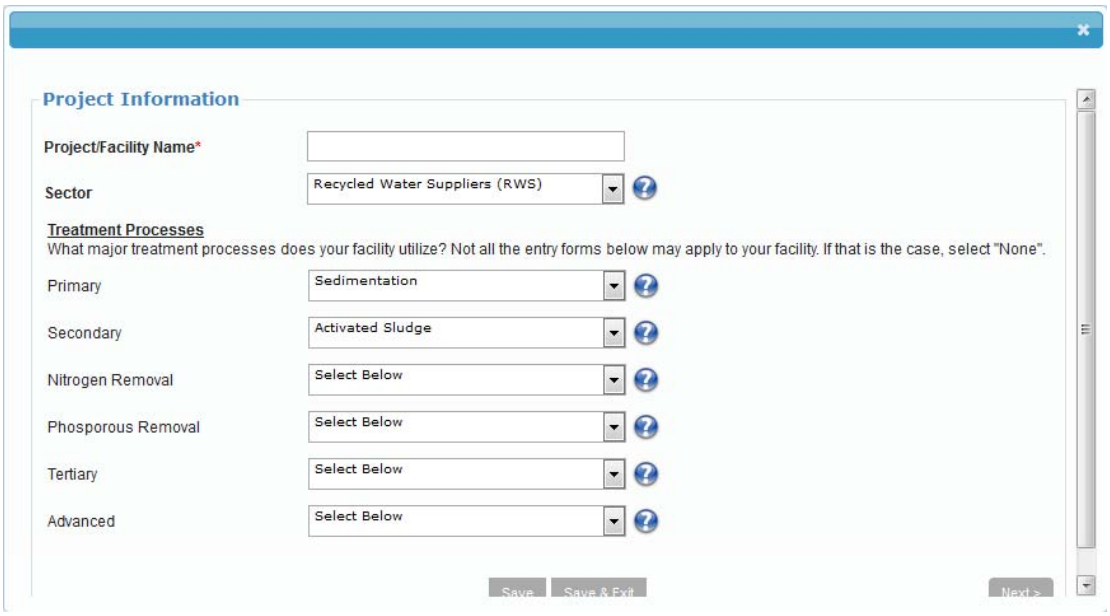

Figure 5.6. Example interface, recycled water supplier, treatment process screen.

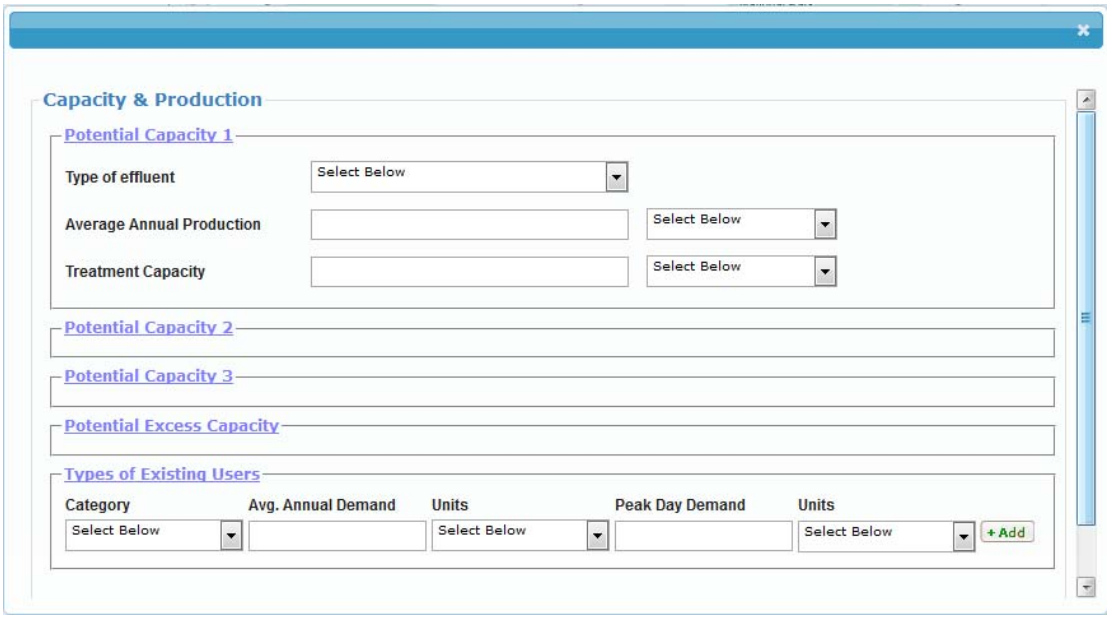

Figure 5.7. Example interface, recycled water supplier, capacity screen.

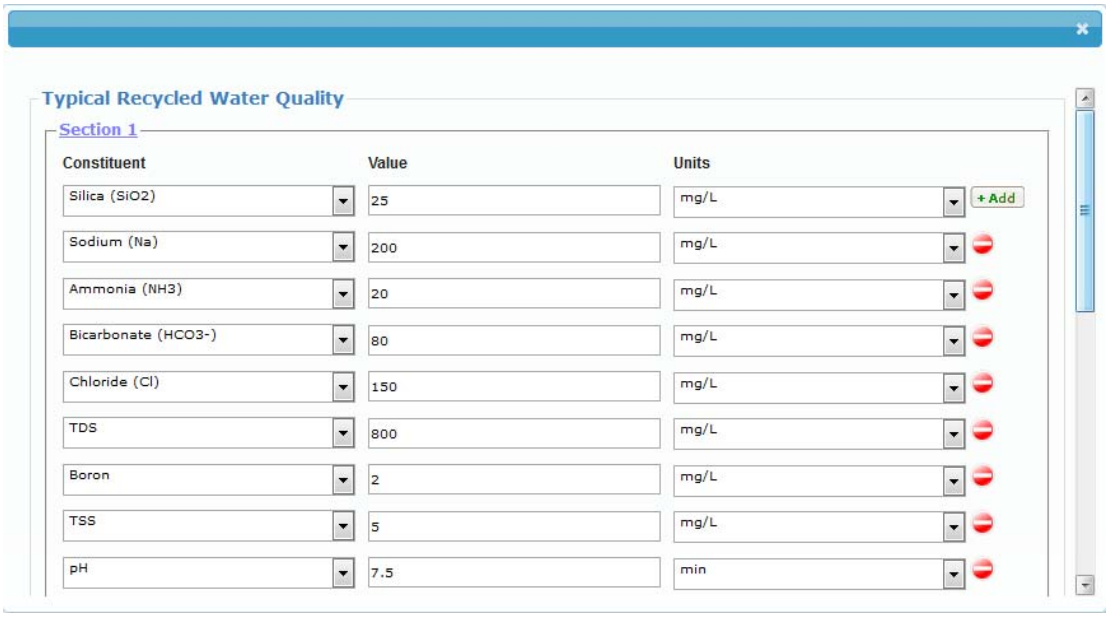

Figure 5.8. Example interface, recycled water supplier, typical water quality.

5.6.2 Initial Recommendations

After the user enters specific data in the forms, the information from those entries will be used to provide some initial recommendations, depending on the type of user (i.e., from the four energy sectors or the recycled water industry). For example, a representative from a biofuels production project would have entered the facility's current or projected production, water quality

requirements, and project location. From these entries, the tool will provide recommendations on what level of treatment is required, the estimated flow of recycled water, and, using cost curves, the cost of that treatment.

For a recycled water supplier, the recommendations will include the type of demands that can be met by its current recycled water quality and how much of those demands can be met by their existing treatment capacity. The recommendations will also provide guidance on what type of demands could be met with additional levels of treatment and provide screening-level cost estimates for those processes.

5.6.3 Interactive Map Screen

Following the initial recommendations screen, the user is directed to the interactive map screen, centered on the location that the user entered in the forms (see Figure 5.9). From here, the user can simply browse the vicinity of the project, selecting layers showing the locations of wastewater treatment plants (sources of recycled water) and other existing or planned facilities in the four energy sectors.

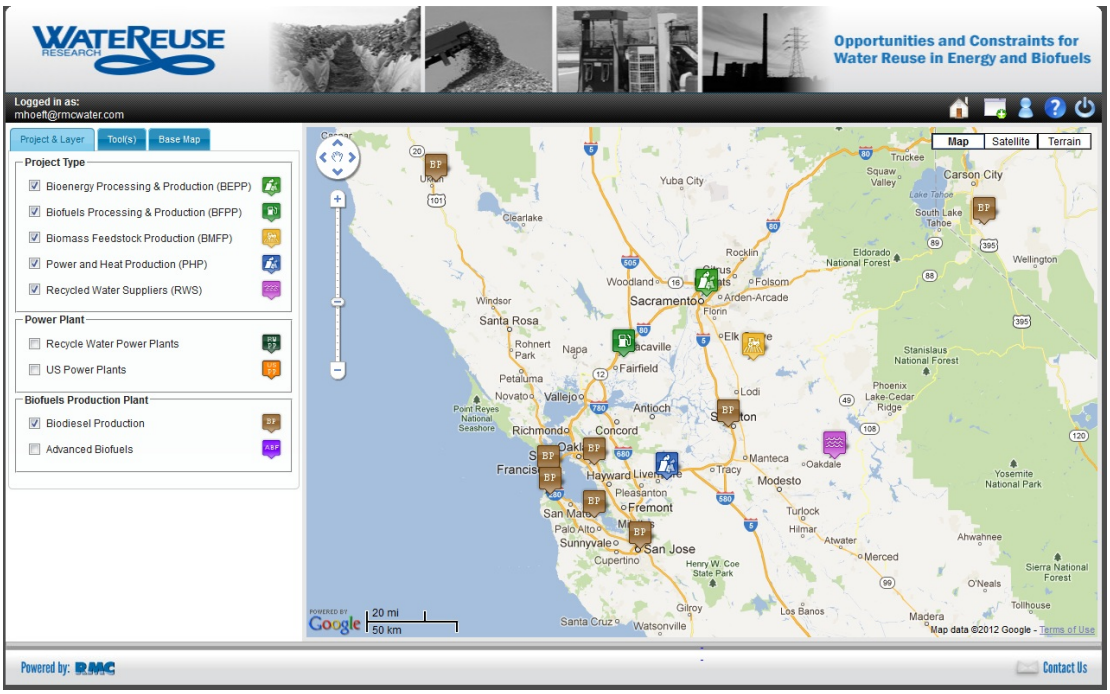

Figure 5.9. Interactive map screen.

Chapter 6

Conclusions and Recommended Next Steps

In recent years, development of new energy technologies has accelerated in an attempt to provide alternatives to traditional, fossil fuel–based methods. At the same time, the continued expansion of traditional energy and fuel production methods has brought attention to the interrelationship of water and energy, known as the Water–Energy Nexus. This report is an attempt to determine what role water recycling and reuse can play in these emerging energy industries as they grow and available water supplies dwindle.

The four energy sectors covered by this report hold significant potential for expansion of water reuse.

- PHP includes industries that have already taken advantage of recycled water as a water supply source. The power generation industry has an established history of plants using recycled water for cooling tower make-up (EPRI, 2008a; Veil, 2007), and those examples can be applied to both traditional, fossil–fuel based power plants and emerging, alternative-fuel power plants such as CSP.

- The BFPP sector covers a variety of biofuels made from various feedstocks, of which the commercially established forms are corn-based ethanol and traditional biodiesel. Corn-based ethanol requires water as slurry media, cooling tower make-up, and boiler feed. Traditional biodiesel requires water for boiler feed and cooling. These demands can be met with recycled water. So-called advanced biofuels include an even wider range of feedstocks and processes, none of which have been successfully commercialized; as a result, less is known about the potential for recycled water demands for these technologies.

- The BEPP sector includes the use of biomass for power generation. Recycled water can be used similarly as in the PHP sector, mostly as cooling tower make-up or boiler feed. The quantity of demands, on an industrywide basis, will be less than that of the PHP sector because of the limited opportunities for BEPP projects and facilities in comparison.

- For the BMFP sector, recycled water can be used for irrigation of biomass crops and growth media for algae. Irrigation of agricultural crops with recycled water has been practiced successfully in California and Florida and can be applied readily to biomass feedstock crops. The potential for recycled water irrigation is highest for corn and soybeans, in particular in arid areas and those with limited water supply availability. Algae can accept lower quality water and can even thrive in secondary effluent, but commercialization of algae cultivation as a biomass feedstock (and precursor to biofuels) has not been established. Therefore, the potential for use of recycled water for algae cultivation is still uncertain.

Of the four energy sectors, PHP has both the most established instances of recycled water use and the highest potential because water demands are so great. However, within the other three sectors and even within certain industries and technologies within PHP, there is great uncertainty as to what technologies will thrive and therefore what opportunities for water reuse will come to

fruition in the near term. For example, just within the span of this project, several planned and permitted CSP projects in California were withdrawn in favor of solar PV power generation. Advanced biofuels, although showing lots of potential and securing substantial investment, have no commercial-scale production facilities in the United States, and many projects scheduled for completion have been delayed or cancelled. As a result, the market for biomass feedstocks has not developed, and neither have the related potential water demands.

Table 6.1 summarizes the best opportunities for recycled water projects as described in Chapter 3. The estimates for potential demands here are high-end estimates that will never be fully met with recycled water supplies but serve to show the magnitude of potential water demands that could be met with recycled water before considering project- and site-specific technical, economic, social, and institutional factors.

6.1 Recommendations

As interest in the Water–Energy Nexus has grown because of valid concerns about the interplay of water and energy in our society, so collaboration between the water and energy industries has grown. Industry groups such as the WateReuse Research Foundation and EPRI have been active in this collaboration. To increase actual projects that implement recycled water use in power, biofuels, bioenergy, and biomass projects, more collaboration must happen at the facility-planning level. With the goal of increasing this collaboration, we offer the following recommendations for those interested in pursuing potential recycled water projects within the four energy sectors.

1. **Target projects where the user is close to the supplier.** The projects most likely to be cost effective for both the recycled water supplier and user are those where the source of water is close to the point of use. Many of the established projects that utilize recycled water for uses found similarly in the four energy sectors involve users that are nearby. If distribution infrastructure and power are required to convey recycled water to the use site, the costs can make the project less attractive.

2. **Target new facilities.** Use of recycled water in many of the ways highlighted in this study requires either equipment suited to the water quality of recycled water or additional treatment. Designing a facility and selecting equipment with recycled water specifically in mind avoids the need for costly retrofits that may be required for existing facilities. Fortunately, because so many of the industries covered by this study are growing, opportunities for recycled water projects will likely arise in the next few years.

3. **Partner with regulators**. Any potential project, whether a new power plant, biofuels production plant, or algae production pond, will require approval from various regulatory agencies. Recycled water suppliers should collaborate with regulatory agencies regarding the use of recycled water for new projects as a way to promote recycled water, increase awareness of recycled water for both the regulators and project representatives, and gain awareness of potential projects in their area. Partnering with agencies may increase the likelihood that they will emphasize the need to utilize recycled water rather than other supplies as they review the project for approval and will educate those applying for approval about the benefits of recycled water. Another potential challenge for recycled water suppliers in identifying potential recycled water customers in the four energy sectors is lack of information about these projects during the planning stages, but collaboration with regulators can increase knowledge during these stages, increasing the likelihood of opportunities for recycled water use.

4. **Use existing experience as guidance for future projects**. Despite the fact that many of the industries covered within the four energy sectors involve emerging technologies, the water demands that offer the largest potential quantities, including cooling tower make-up, boiler feed, and irrigation, all have existing, established facilities with success using recycled water that can serve as examples for future projects. Stakeholders of these successful projects would advance the cause of expanding recycled water use by outreach to industry groups in both the recycled water world and the four energy sectors.

5. **The tool** created as part of this project will help to foster relationships between those in the recycled water industry and he four energy sectors. The tool will act as a guide to either users or recycled water supplies in proximity to potential projects and help to connect these two sides of the Water–Energy Nexus. The tool will be available on the California Energy Commission and WateReuse Foundation Websites in an effort to promote collaboration and exchange of ideas as a starting point for potential projects.

Table 6.1. Potential Demands for Recycled Water in the Four Energy Sectors

Category of Water Demand	Potential Demand (MGY)	Challenges to Implementation of Recycled Water Supply Projects
Power & Heat Production		
Projected new power plants		
Natural gas	26,000	Proximity to wastewater/recycled water supply sources Coordination between power plant developers and recycled water suppliers Cost related to treating and conveying the water to the plant site Cooling systems designed for different water quality than recycled water, resulting in costly retrofits, high chemical use, or reduced cycles of concentration Widespread implementation of CCS is not likely in the near term without implementation of enforceable GHG emissions regulations, which have not yet been issued (regulations are in development in California). Large-scale carbon capture and storage has not been widely applied in the industry; therefore, true power penalty and water demands may vary from this estimate.
Coal	--	
Nuclear power	111,000	
Geothermal	91	
Biogenic municipal waste	237	
Concentrating solar	1600	
Solar photovoltaic	35	
Replace existing power plant water source with recycled water[1, 2]	up to 73 million	
Implementation of carbon capture & storage	up to 14 million	
Bioenergy Processing & Production		
New biomass direct firing plants	3700	Proximity to wastewater/recycled water supply sources. Coordination between power plant developers and recycled water suppliers Cost related to treating and conveying the water to the plant site
New biomass co-firing plants[3]	up to 37,200	

Biofuels Processing & Production		
Projected new production plants		Proximity to wastewater/recycled water supply sources
Ethanol, corn and starch	23,000	Coordination between biofuel production facility developers and recycled water suppliers
Ethanol, cellulosic	19,000	Cost related to treating and conveying the water to the plant site
Biodiesel	3,000	Success of Renewable Fuels Standards or other regulations and incentives to promote the production of advanced biofuels
Other advanced biofuels[4]	Uncertain	Development of viable, commercial-scale production methods (for cellulosic and other advanced biofuels)
Biomass Feedstock Production		
Corn irrigation[5]	up to 3.9 million	Cost of existing irrigation water supplies are typically orders of magnitude lower than typical cost of recycled water supplies.
Soybean irrigation[5]	up to 1.6 million	Proximity to wastewater/recycled water supply sources
Cellulosic crop irrigation[6]	Uncertain	Cost related to treating or conveying the water to the irrigation site
Algae cultivation, near term	limited[7]	Best opportunities exist where noneconomic factors drive use of recycled water (e.g., discharge requirements)
Algae cultivation, long term[8]	up to 7.4 million	

Notes: 1=Potential demand is based on Kenny et al., 2009, estimate of total water withdrawals in the United States for electricity generation. 2=92% of existing water withdrawals for power plant cooling is for once-through cooling systems; recycled water is rarely available in quantities to meet withdrawal demands of once-through cooling. 3=Growth in co-firing will be due in part to implementation at existing fossil fuel–based power plants, so this potential demand partially overlaps with estimates in the PHP sector. 4=Industrywide data not available. Production processes for advanced biofuels have not been widely commercialized. 5=Estimates for corn and soybean irrigation is based on total U.S. irrigation water used for each crop per the USDA Farm and Ranch Irrigation Survey (2008). 6=No data available for U.S. total irrigation use for cellulosic crops. 7=Algae cultivation for commercial production in the near term is expected to be limited. 8=Estimates are based on analysis in Wigmosta et al. (2011) on the basis of U.S. advanced biofuels target per the Energy Independence and Security Act of 2007.

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APPENDIX B:
Renewable Energy, Peak Power Management, and Optimization of Advanced Treatment Technologies to Reduce Greenhouse Gases at Water Reuse, Desalination and Wastewater Membrane Treatment Plants

Renewable Energy Technologies and Energy Efficiency Strategies

About the WateReuse Research Foundation

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

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

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

Renewable Energy Technologies and Energy Efficiency Strategies

Guidebook for Water Desalination and Reuse Systems to Optimize Energy Use and Reduce Green House Gas Emissions

Joseph Jacangelo, Ph.D.
MWH

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Alexandria, VA

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Acronyms and Abbreviations

AC	alternating current
AFC	alkaline fuel cell
AOP	advanced oxidation process
APP	axial piston pumps
ARRA	American Recovery and Reinvestment Act
AWT	advanced water treatment
BCRS	brine concentration and recovery system
BEP	best efficiency point
BNR	biological nitrogen removal
CARROT	Climate Action Registry Online Tool
CCAR	California Climate Action Registry
CCD	closed circuit desalination
CCX	Chicago Climate Exchange
CDI	capacitive deionization
CDM	Clean Development Mechanism
CEDI	continuous electrodeionization
CERCLA	Comprehensive Environmental Response and Liability Act
CIGS	copper indium gallium diselenide
CONVAS	conventional activated sludge
CPV	concentrator photovoltaic
CREB	Clean Renewable Energy Bond
CSP	concentrating solar power
CWA	Clean Water Act
DC	direct current
DNA	deoxyribonucleic acid
DST	decision support tool
DW	drinking water
DWEER	dual work exchanger energy recovery
EBOP	electrical balance of plant
ED	electrodialysis
EDR	electrodialysis reversal
EPC	engineering, procurement, and construction
ERD	energy recovery device

ESPC	energy savings performance contracts
ESS	energy storage systems
FO	forward osmosis
GEO	Geothermal Exchange Organization
GFD	gallons/square foot/day
GGRT	Greenhouse Gas Reporting Tool
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GWP	global warming potential
GWR	ground water replenishment
HD	humidification–dehumidification
HVAC	heating ventilation and air conditioning
ICLEI	International Council for Local Environmental Initiatives
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power provider
IPR	indirect potable reuse
ISO	International Organization for Standardization
ITC	investment tax credit
ITP	Industrial Technologies Program
LCZ	lower convecting zone
MBOP	mechanical balance of plant
MBR	membrane bioreactor
MCDI	membrane–CDI
MCFC	molten carbonate fuel cell
MD	membrane distillation
MED	multieffect distillation
MEH	multieffect humidification
MEMS	multieffect multistage
MF	microfiltration
MGD	million gallons per day
MLSS	mixed-liquor suspended solids
MPN	most probable number
MSF	multistage flash
MVC	mechanical vapor compression

NCZ	nonconvecting zone
NEPA	National Environmental Pollution Act
NPDES	National Pollution Discharge Elimination System
NYSERDA	New York State Energy Research and Development Authority
O&M	operation and maintenance
OEEP	Operational Energy Efficiency Program
PACE	property assessed clean energy
PAFC	phosphoric acid fuel cell
PEFC	polymer electrolyte fuel cell
PEM	polymer electrolyte membrane
PSAT	pump system assessment tool
PSB	polysulfide bromide flow battery
PPA	power purchase agreement
PSIM	pump system improvement modeling
PTC	production tax credit
PV	photovoltaic
PWE	pressure or work exchanger
PWT	Pelton wheel turbine
PX	pressure exchanger
QECB	qualified energy conservation bond
RDSI	renewable and distributed systems integration
REC	Renewable Energy Credit/Certificate
ReEDS	Regional Energy Deployment System
REPI	renewable energy production incentive
RNA	ribonucleic acid
RO	reverse osmosis
ROI	return on investment
RPS	renewable energy portfolio standard
RRTP	reverse-running turbine pump
SCADA	supervisory control and data acquisition
SDWA	Safe Drinking Water Act
SEGIS	solar energy grid integration systems
SOFC	solid oxide fuel cell
SOP	standard operating procedure
SRT	sludge retention time
SWRO	seawater RO

TBP	turbo-booster pump
TDS	total dissolved solids
TVC	thermal vapor compression
UCZ	upper convecting zone
UF	ultrafiltration
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
UV	ultraviolet
VC	vapor compression
VFD	variable frequency drive
VRB	vanadium redox flow battery
WBSCD	World Business Council for Sustainable Development
WRI	World Research Institute
WRP	water recycling plant
ZBR	zinc bromine flow battery

Foreword

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

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

- Defining and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

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

The Foundation's primary funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and other funding relationships.

The overall objectives of this project were to develop a comprehensive knowledge base for utilities in the United States, with the most updated developments in energy minimization and renewable energy techniques, and to prepare an easy-to-understand guidebook based on the relevant practical lessons learned by global researchers, organizations and utilities.

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Executive Summary

Purpose and Objective

The purpose of this guidebook is to provide utilities and water treatment practitioners with energy minimization strategies and renewable energy utilization guidelines. The guidebook is primarily focused on desalination using reverse osmosis (RO) and advanced water treatment (AWT) technologies. The overall objectives of this project were to develop a comprehensive knowledge base for utilities in the United States, with the most updated developments in energy minimization and renewable energy techniques, and to prepare an easy-to-understand guidebook based on the relevant practical lessons learned by global researchers, organizations, and utilities. The guidebook was developed as part of WateReuse Research Foundation Project WRF-08-13. The guidebook delineates analytical and quantitative guidelines for technologies to reduce energy use, overall facility costs, and greenhouse gas (GHG) emissions from AWT processes used in water reuse and desalination.

Research Approach

The project consisted of three major phases: (1) literature review, (2) utility case studies, and (3) guidebook development. During Phase 1 of the project, a thorough literature review of energy minimization strategies and renewable energy implementation for desalination and water reuse facilities was undertaken. During Phase 2 of the project, desalination and water reuse utilities with conventional and renewable energy resource utilization were surveyed. Information pertaining to the challenges and lessons learned in the process, energy minimization approaches, and renewable energy implementation was obtained. During Phase 3 of the project, information gathered from the literature review and utility survey were used to prepare this guidebook on energy minimization and renewable energy implementation strategies.

Findings and Conclusions

Energy usage can impact a utility in several areas of operation. Reducing energy consumption can lead to both reduced energy costs and GHG emissions. A combination of several strategies needs to be considered to reduce energy consumption. These strategies include improved system design, utilization of high-efficiency pumping, implementation of energy recovery devices (ERDs), and non-process-related conservation. Pumping consumes the largest energy for desalination using RO. All the energy minimization strategies and technologies are well developed and proven. Implementation of energy-efficient strategies can result in significant energy savings for the treatment plant. Development of an energy core team that understands the energy usage of the utility will be key to implementing these strategies. Implementation of energy efficiency programs should be performed with an energy audit to assess baseline energy consumption. Energy minimization approaches need to be considered during the initial design phase of the project, plant operation, retrofits and process modification, plant expansion, and treatment scheme upgrades.

Utilization of renewable energy technologies depends on the geography, technology, and means of handling variability, and solving economic scale-up and permitting issues. Technologies such as solar photovoltaic, concentrating solar power, wind turbines, geothermal energy, and biogas cogeneration are well developed but are still expensive to implement without the availability of funding, grants, and incentives. Return on investment (ROI) is a key criterion and decision maker for the implementation of renewable energy technologies at the utility scale.

A well-thought-out energy minimization plan that includes renewable energy utilization will reduce energy costs, positively impact the environment, and show a strong commitment to environmental stewardship and conservation of natural resources.

Chapter 1

Introduction

1.1 Water Demand and Consumption

The production of potable water has become a worldwide concern today. Less than 3% of the earth's 330 million cubic miles of water is freshwater and it is very unevenly distributed across the planet. For many communities, projected population growth and demand exceed freshwater resources (Greenlee et al., 2009). It is estimated that over 1 billion people are without clean drinking water and approximately 2.3 billion people live in regions with water shortages (Service, 2006). As a result of demographic expansion, many areas in the world face the challenge of meeting ever-increasing water demands.

Global water consumption trends project more than 750 billion m^3 per year of water consumption by 2025 for North America alone (USGS, 2005). In the United States, the highest water consumption is in California, where more than 45,000 million gallons per day (MGD) of water is withdrawn predominantly for irrigation, thermoelectric power generation, and public supply (USGS, 2005). To cope with this increasing water demand, many municipalities and other water suppliers are turning toward more energy-intensive seawater desalination and water reclamation to supplement dwindling freshwater sources.

1.2 Desalination and Water Reuse

Desalination and water reuse technologies have been successfully implemented to provide additional freshwater production for communities (USEPA, 2004; Gleick, 1996; Sandia National Labs, 2003; Gleick, 2006). In the U.S., most desalination facilities are designed to achieve a total dissolved solids (TDS) content of 500 mg/L or less in the product water (permeate), for which reverse osmosis (RO) technology is predominantly used (Greenlee et al., 2009). The majority of plants in Saudi Arabia, the United Arab Emirates (UAE), and other Middle East countries use thermal processes, such as multistage flash (MSF), multieffect distillation (MED), and vapor compression (VC), producing TDS of less than 50 mg/L (Ettouney et al., 1999; Greenlee et al., 2009).

A forecast by the *Economist* magazine of global desalination technology utilization predicted that the global capacity of RO technology will outpace that of thermal desalination facilities (*The Economist*, 2008). Domestically, desalination accounts for approximately 0.4% of total water production capacity. Over 75% of U.S. desalination capacity is used to treat brackish groundwater or river water. Coastal and arid states including Florida, California, Texas, and Arizona have the highest installed desalination capacities in the U.S (Wangnick and GWI, 2005).

When water reuse is concerned, meeting stringent drinking water regulations requires the use of AWT technologies. Examples of AWT technologies being used or considered for both water and wastewater applications include ozonation, ultraviolet (UV) disinfection, and membrane processes (Chang et al., 2008). Membrane processes can involve a combination of low-pressure (microfiltration, ultrafiltration, membrane bioreactors) and high-pressure membrane processes (reverse osmosis).

AWT technologies are also used for indirect potable reuse (IPR) applications. IPR is the practice of taking recycled water that meets all regulatory requirements for nonpotable use, treating it further with several AWT technologies to meet potable water standards, and adding it to an untreated potable water supply. Indirect potable reuse typically refers to a combination of microfiltration (MF)/ultrafiltration (UF) followed by RO and UV disinfection. For advanced water treatment and reuse, the capital expenditure in the U.S. is predicted to grow by 19.5% over the next six years (Water Desalination Report, 2009). The cumulative installed water reuse capacity for IPR is expected to be almost 1.06 billion gallons per day by the year 2016 (Water Desalination Report, 2009).

Energy consumption in desalination and water reuse processes is of particular concern because of the rising cost of electricity. Although equipment costs have been decreasing as a result of technological advancements, the cost of energy continues to escalate. For example, because of significant reductions in membrane equipment and material costs over the last 20 years, energy consumption is now the second largest fraction of unit water cost in RO applications (Chang et al., 2008). Improving the energy efficiency of desalination and water reuse processes requires that a comprehensive understanding of energy consumption by the different equipment be developed. Key to improving the energy efficiency of desalination and water reuse processes is understanding their important characteristics, such as determining the primary energy-consuming equipment, water quality, and operating parameters that are influencing energy consumption.

Until recently, conventional fossil-fuel-based power plants have been utilized as the primary source for supplying energy to desalination and water reuse plants. However, the use of fossil fuels for generating power has spurred environmental concerns, specifically with GHG emissions. Thus, there are a large number of energy minimization approaches and renewable energy alternatives being developed, investigated, and implemented around the globe for desalination and water reuse applications.

1.3 Objectives of the Guidebook

The objective of this guidebook is to provide utilities and water treatment practitioners with strategies for energy minimization and renewable energy utilization.

This guidebook was developed to answer the following questions:

- What are the steps and methods to reduce energy consumption for various membrane-based desalination and advanced water treatment processes?
- What are the resources and tools available in pursuing energy efficiency at a treatment facility and in renewable energy resource implementation?
- What are the steps required for utilizing renewable energy resources?
- What are the challenges faced during implementation of renewable energy technologies?

1.4 Organization of the Guidebook

This guidebook is organized into the following chapters:

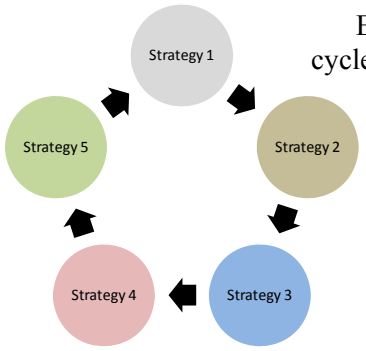
- Chapter 1: Introduction
- Chapter 2: Planning
- Chapter 3: Implementation of Energy-Efficient Strategies
- Chapter 4: Utilization of Renewable Energy Resources

Each chapter comprises objective, essential components for implementation, implementation steps, resources, and tools. Information obtained from the utility survey and literature review was utilized to develop the guidebook contents. Information from the utility survey and case studies is provided as Appendix A. More detailed descriptions of the process and energy minimization strategies are provided in Appendix B. Detailed descriptions of renewable energy utilization and GHG emissions are provided in Appendix C.

1.5 How to Use the Guidebook

The strategies provided in the guidebook are best utilized during the concept development and design phase of a project, but the guidelines can also be implemented during routine process operations and maintenance periods. The guidebook can be utilized for new treatment facility design, upgrades, and retrofits to existing treatment facilities to improve energy efficiency. Every chapter and its contents are provided with a resource section with information on tools available for design and implementation, resource guides, technology updates, and vendor information.

1.6 Purpose of Icons



Each chapter in the guidebook is provided with a basic cycle figure that consists of the components and strategies that need to be considered for energy minimization and renewable energy utilization. Consideration of all the components in a holistic manner will provide the best benefits to the user.

The light bulbs in the chapters suggest important information that needs to be considered in developing energy minimization and renewable energy utilization strategies.

The magnifying glass provides further resources and tools for the various components of the guidebook. The resources contain webpage links that can be accessed to gather additional useful information on a particular topic.

Chapter 2

Planning

In this chapter, key components required for planning energy minimization and renewable energy utilization in a treatment plant are discussed. Steps required for energy efficiency management and renewable resource utilization are outlined. Additional resources for planning and auditing energy efficiency management and renewable resource utilization are provided at the end of the chapter.

2.1 Benefits of Implementing Energy Efficiency and Renewable Energy Utilization

Many benefits can be among the drivers for implementing these changes at a treatment plant:

- *Financial savings:* Reducing energy consumption will result in significant cost savings for the utility in terms of its energy bill.
- *Reduced GHG emissions:* Implementation of renewable energy resources will result in lower GHG emissions by reducing the consumption of fossil-fuel-based electricity.
- *Meeting state and federal energy-reduction targets:* Reduction of energy consumption will result in meeting targets set by local and federal authority for energy utilization.
- *Environmental stewardship:* Utilization of renewable energy resources will result in a clean and sustainable environment for the public.
- *Improved customer relations:* By implementing green initiatives and carbon-neutral treatment, facilities will improve utility–customer relationships.

2.2 Steps to Energy Efficiency and Renewable Energy Utilization

The steps that are typically followed for energy efficiency and renewable energy utilization are summarized in Figure 2.1. These steps are management, collection, implementation, monitoring and reporting, and continual improvement. These steps are then further expanded on in the subsections.

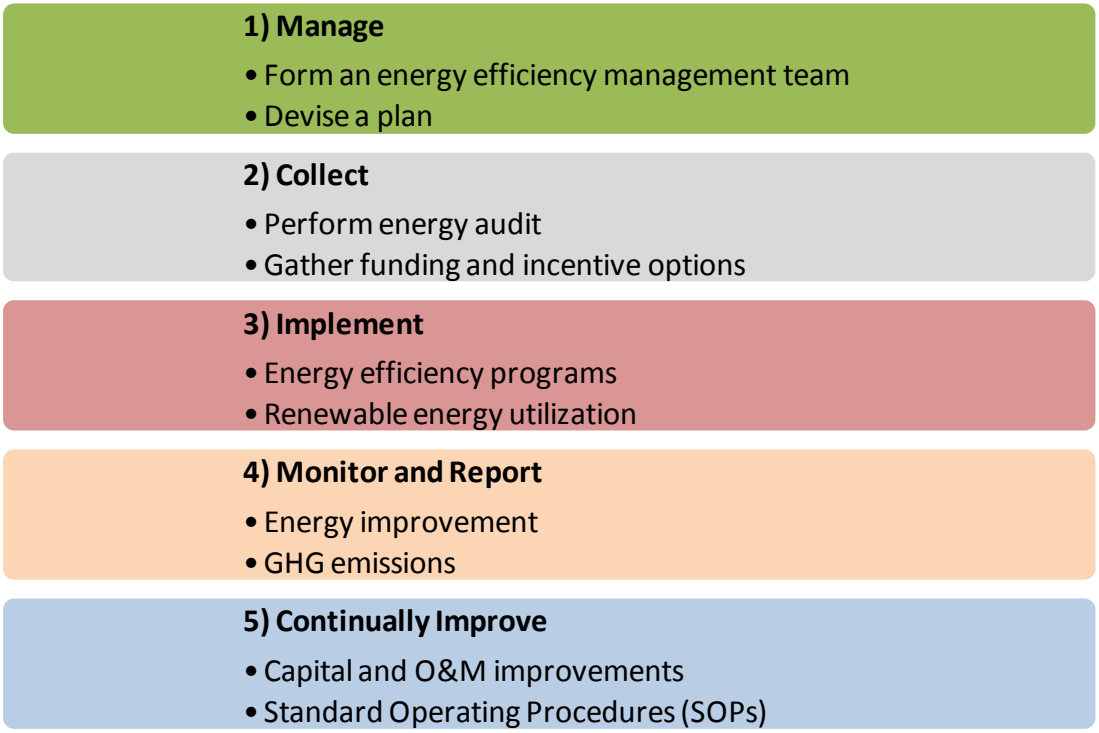


Figure 2.1. Steps involved in energy efficiency and renewable energy utilization.

Step 1. Manage

The first step is to create an organizational structure, such as a core management team, to manage and be accountable for any efficiencies or recommendations decided on. This team should consist of an energy program manager and staff who will be actively engaged in achieving the determined goals.

- *Energy program manager:* The energy program manager will have the responsibility and management authority for implementing energy improvement programs and renewable energy resource utilization from start to finish.
- *Energy team:* The core team should consist of personnel who have knowledge of utility processes and energy usage and will help communicate the importance of energy improvement to utility staff. By creating a core energy team, you will have people to focus on monitoring energy efficiency and implementation goals. The energy team should consist of personnel who can assist during design, operation, and maintenance of the treatment plant.
- *Construct a plan:* Utilize the program manager and energy team to develop methods to improve energy management, implement renewable energy resources within a specific timeline, and develop a plan for periodic monitoring of energy efficiency and GHG emissions of the plant.

Step 2. Collect

The second step is to collect energy consumption data from the plant. Collection of data should be performed through an energy audit. Information collected through the energy audit can be used to set up a baseline for energy consumption and necessary energy improvements. Although considering energy efficiency management and renewable energy resource utilization, the collection step should also include an assessment of various financial options that are available for successful implementation of the schemes.

- *Energy audit:* Have the energy team perform an energy audit to determine the baseline energy demand and consumption of the plant. The energy audit can be used to identify areas that require the greatest attention. Walk-through process audits provide an initial assessment of energy savings and determine if a detailed process audit should be undertaken at a facility. Detailed process audits are an extension of the walk-through audit and can be performed by an electricity utility representative, water or wastewater agency staff, or an external energy audit specialist. Various tools for performing an energy audit are provided in the additional resources section at the end of this chapter.
- *Funding options:* The energy team can also identify funding options and incentives available for implementing renewable energy at the facility and set a budget for energy improvement and renewable energy utilization. Various funding options available are discussed in Chapter 4 of the guidebook.

Step 3. Implement

The third step is the identification of the correct technologies for energy efficiency and renewable energy and their implementation at the utility. Identification of strategies for the implementation of selected energy-efficient schemes is discussed in Chapter 3. Identification and strategies of renewable energy utilization are provided in Chapter 4. In implementing the strategies, consider the following:

- Options available for renewable energy utilization
- Implementation of monitoring and report systems for measuring and tracking energy efficiency and renewable energy utilization

Step 4. Monitor and Report

The fourth step involved is monitoring and reporting the information collected from the various processes and for calculating GHG emissions. Various tools available for monitoring and reporting are provided in the additional resources section at the end of this chapter.

- *Monitor:* Initiate a program to monitor energy metrics continuously. This may occur on a periodic basis—for example, a planned annual update. Monitoring may also be performed continuously through existing SCADA (supervisory control and data acquisition) and data management systems.
- *Energy improvement:* Report improved energy efficiency and cost savings.
- *GHG emissions:* Report GHG emissions of the entire plant and their associated processes.

- *Public outreach:* Disseminate information on the energy efficiency achieved and the renewable energy utilized. This information should include energy efficiency before and after implementation of energy efficiency programs and GHG emission amounts before and after utilization of renewable energy resources.

Step 5. Continually Improve

The final step is to continually improve the established goals for energy management and renewable resource utilization. Development of an energy policy will result in the utility's commitment to improved energy use and management of resources. The energy policy should be developed specifically for the utility to accomplish these goals.

- *Continuous improvement:* To ensure that all future capital improvements and operation and maintenance (O&M) upgrades continue to meet energy efficiency requirements and goals, a continuous improvement process needs to be carried out.
- *Standard operating procedures (SOPs):* SOPs set in place standard practices for evaluating energy efficiency of all capital additions and O&M improvements.

Additional Resources

Guidebooks

Handbooks for energy efficiency:
http://www.energy.ca.gov/reports/efficiency_handbooks/index.html. Last accessed: July 11, 2011.

> Information is provided on energy accounting, financing public sector energy projects, energy auditing, guidelines for hiring an energy service company and guidelines for hiring a construction manager.

Energy management guidebook for wastewater and wastewater utilities:
http://www.epa.gov/region6/water/energymgt/energy_mgt_guidebook_wastewater.pdf. Last accessed: July 11, 2011.

> This guidebook provides a methodology for energy monitoring, energy minimization, and energy improvement for public utilities.

Energy best practice guidebook for water and wastewater utilities:
http://www.werf.org/AM/Template.cfm?Section=Home&TEMPLATE=/CM/ContentDisplay.cfm&CONTENTID=10245. Last accessed: July 11, 2011.

> This guidebook provides guidelines on energy use estimation, energy baseline calculations, management and technical best practices for water treatment, wastewater treatment, and collection and distribution systems.

Energy Auditing

Determining baseline energy use:
http://water.epa.gov/infrastructure/sustain/baseline_energy.cfm. Last accessed: July 12, 2011.

> By determining baseline energy use, utility managers and operators can better understand their electricity providers' rate structure and understand how current operations impact energy consumption. The web link provides information on protocols for conducting energy audits, an energy self-assessment tool and funding resources for implementing energy efficient strategies.

Energy audit manual for water and wastewater facilities:
http://www.cee1.org/ind/mot-sys/ww/epri-audit.pdf. Last accessed: July 12, 2011.

> The energy audit manual provides information on conducting walk-through and process audits, process energy conservation measures (ECM), and monitoring and follow-up procedures on energy management for water and wastewater facilities.

Energy management tool to track and assess water consumption:
http://www.energystar.gov/index.cfm?c=evaluate_performance.bus_portfoliomanager. Last accessed: July 12, 2011.

> This energy management tool can be used to track and assess energy and water consumption across the entire portfolio of buildings in a utility. The portfolio manager can be used to estimate the energy consumption of buildings and the carbon footprint of the utility.

Software tools for energy efficiency best practices:
http://www1.eere.energy.gov/industry/bestpractices/software.html. Last accessed: July 12, 2011.

> The Industrial Technologies Program (ITP) of the Department of Energy provides free software tools to identify and analyze the energy of systems and savings opportunities.

Auditing tools and protocols:
http://cfpub.epa.gov/compliance/resources/policies/incentives/auditing/. Last accessed: July 12, 2011.

> Auditing policies and protocols for utilities under various programs, such as the Safe Drinking Water Act (SDWA), Clean Water Act (CWA), Comprehensive Environmental Response and Liability Act (CERCLA), can be found at this web link.

Monitoring and Reporting

Climate Action Registry Online Tool (CARROT):
http://www.climateregistry.org/tools/carrot.html. Last accessed: July 12, 2011.

> CARROT is a web-based tool that is used for calculating and monitoring GHG emissions at the utility. CARROT uses built-in emission factors and conversion factors to automate calculation of GHG inventories and improve consistency and comparability. Users input annual energy usage data (i.e., kWh of electricity, or MMBtu of natural gas) and CARROT calculates the associated GHG emissions.

Electronic Greenhouse Gas Reporting Tool (e-GGRT):
http://www.epa.gov/climatechange/emissions/ghgrulemaking.html. Last accessed: July 12, 2011.

> The EPA issued the Mandatory Reporting of Greenhouse Gases Rule (74 FR 5620), which requires reporting of greenhouse gas (GHG) data and other relevant information from large sources and suppliers in the United States. The purpose of the rule is to collect accurate and timely GHG data to inform future policy decisions. In general, the Rule is referred to as 40 CFR Part 98 (Part 98). Implementation of Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP).

GHG monitoring guidelines:
http://www.commerce.wa.gov/DesktopModules/CTEDPublications/CTEDPublicationsView.aspx?tabID=0&ItemID=7797&MId=944&wversion=Staging. Last accessed: July 12, 2011.

> An assessment of GHG tools currently available is provided in a report prepared for the Department of Commerce of the state of Washington. The assessment compares various GHG tools for mobile and nonmobile source emissions and provides guidelines for selecting the right monitoring tool.

GHG emissions and management tool (opsGHG):
http://www.esp-net.com/Products/opsiEnvironmentalisupTMsup/opsiGHGisupTMsup/tabid/200/Default.aspx. Last accessed: July 12, 2011.

> The opsGHG software helps utilities meet the challenges of GHG monitoring by delivering streamlined tracking, managing, and reporting of direct and indirect greenhouse gas emissions. The software links together with the rest of an environmental information management system to give powerful and complete emissions data management, all from one centralized, web-accessible source.

Carbon dioxide (CO2) emissions from the generation of electric power in the United States:
http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html. Last accessed: July 12, 2011.

> This report was prepared jointly by the staff of the U.S. Department of Energy and the U.S. Environmental Protection Agency.

Calculation of GHG emissions from energy use:
http://www.cleanerandgreener.org/resources/pollutioncalculator.html. Last accessed: July 12, 2011.

GHG emissions can be calculated using the tool provided based on the total energy consumption of the utility in kWh.

Chapter 3

Implementation of Energy-Efficient Strategies

In this chapter, various energy-minimization guidelines for desalination and AWT technologies are provided. The chapter consists of typical energy consumption rates for desalination and AWT treatment processes per unit of water produced. System design, pumping efficiency improvement, utilization of ERDs, energy-saving membranes, membrane configuration, and non-process-related energy components are discussed in detail in the subsections.

Several strategies in combination will need to be used to minimize energy consumption.

Components of the energy minimization of desalination and AWT processes are shown in Figure 3.1. Maximum energy efficiency will be obtained when all the components are considered in a holistic manner. It is critical to understand the distribution of energy by various treatment processes to determine avenues for energy minimization. Distributions of energy for typical desalination and AWT processes are provided in the next two subsections.

3.1 Rates of Energy Consumption by Different Treatment Processes

Understand the distribution and magnitude of energy consumption rates among treatment process components.

Energy consumption rates for different types of desalination and water treatment facilities are listed in Table 3.1. The energy consumption for the seawater desalination and AWT plants listed in Table 3.1 correspond to a plant with process components shown in Figures 3.2 and 3.3, respectively. For a brackish-water desalination plant, groundwater is typically treated directly using brackish-water RO membranes with only cartridge filtration as pretreatment. For wastewater treatment, the process train would typically include primary and secondary treatment. For AWT facilities, the process train would typically include MF/UF, RO, and UV/hydrogen peroxide. Detailed descriptions of various desalination technologies and AWT processes are provided in Appendix B, Sections 1 to 4. Detailed information on energy consumption for desalination and AWT plants is provided by Cooley and Wilkinson (2011). Additional information on energy consumption by various treatment processes is provided in Appendix B, Section 5.

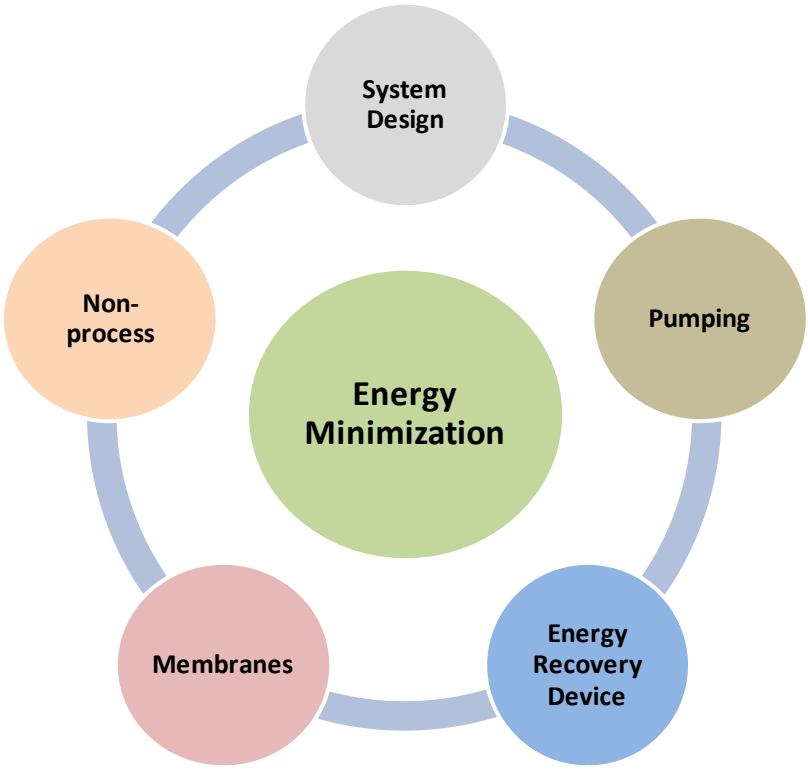


Figure 3.1. Energy minimization for desalination and advanced water treatment requires a holistic approach.

Table 3.1. Typical Energy Consumption for Various Types of Plants (Data Obtained from Utility Survey) in Kilowatt-Hours Consumed per Cubic Meter (kWh/m^3) of Treated Water Produced

Plant Type	Energy Consumption
Seawater desalination	3–4 kWh/m^3
Brackish water desalination	~ 1 kWh/m^3
Wastewater treatment[1]	~0.6 kWh/m^3
Advanced water treatment[2]	~ 1 kWh/m^3

[1]Conventional wastewater treatment plant.

[2]Treatment of secondary/tertiary effluent with RO and UV processes.

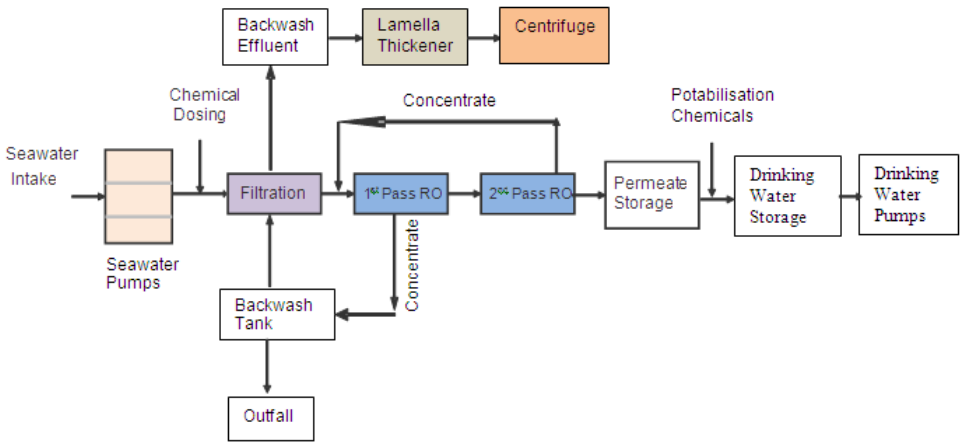


Figure 3.2. Process flow schematic of typical seawater desalination plant.

3.2 Examples of Energy Consumption for Large-Scale Desalination and Advanced Water Treatment Plants

Typical distributions of energy for seawater desalination, brackish water desalination, and advanced wastewater treatment are shown in Figures 3.4, 3.5 and 3.6, respectively. Process train configurations for the energy distribution pie charts correspond to typical plants described in Figures 3.2 and 3.3. For the various types of treatment schemes, energy consumption due to pumping requirements is highest. For desalination, high pressure pumping consumes the maximum energy.

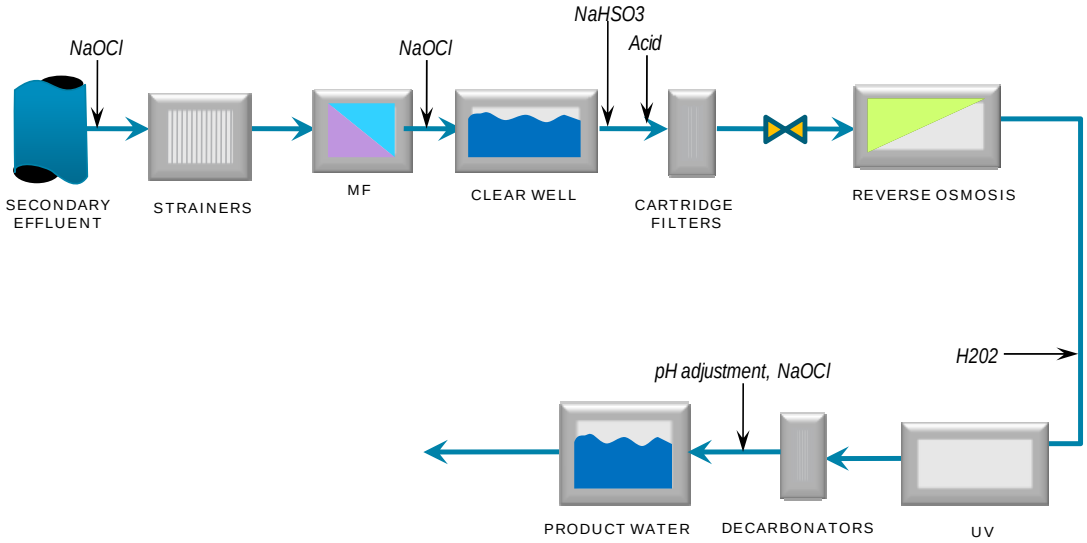


Figure 3.3. Process flow schematic of typical AWT plant.

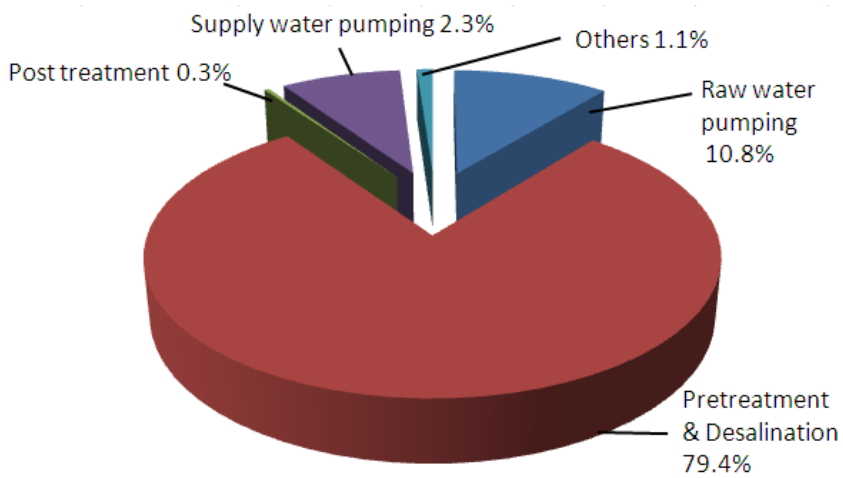


Figure 3.4. Typical distribution of energy for surface seawater RO desalination. (Data obtained from utility survey—Appendix A.) Supply water pumping refers to treated water distribution. Total energy consumption ~3.4 kWh/m^3. *Note:* Distribution of energy does not equate to 100% for these data.

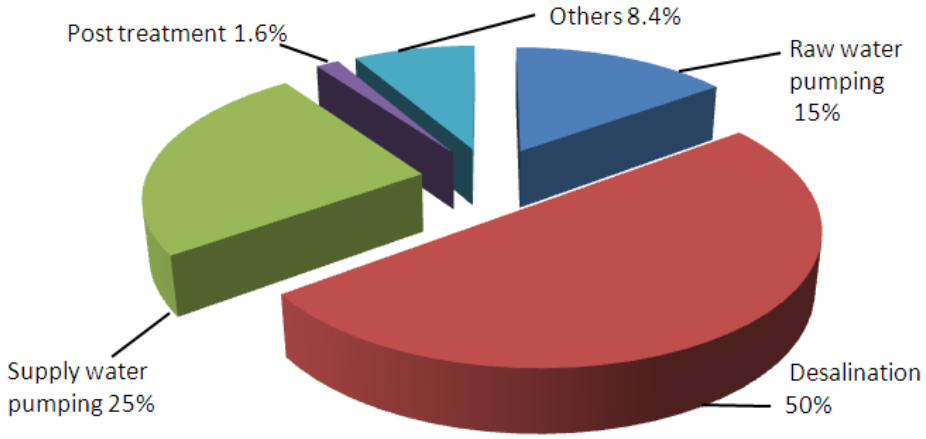


Figure 3.5. Typical distribution of energy for brackish groundwater RO desalination. Total energy consumption ~ 1 kWh/m^3 (Chang et al., 2008).

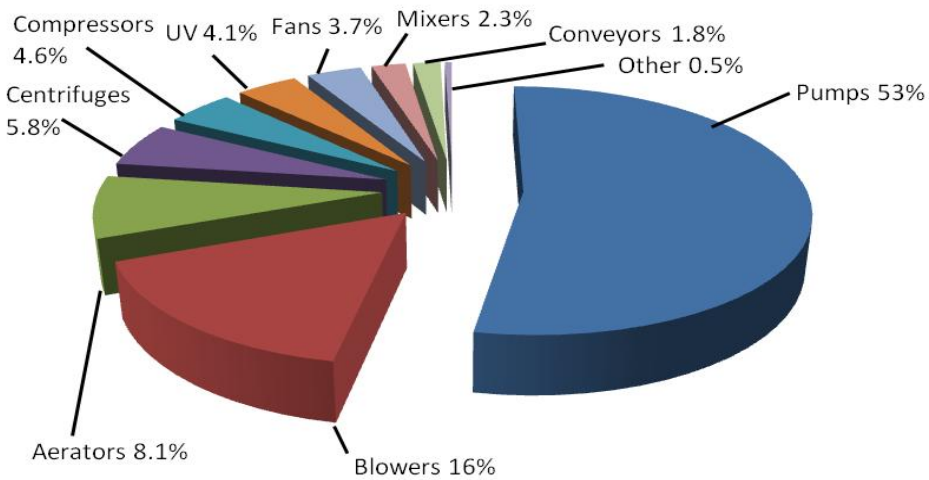


Figure 3.6. Typical distribution of energy for advanced water treatment. Total energy consumption ~1 kWh/m^3. (Data obtained from utility survey.)

3.3 Strategies for Energy Minimization

Strategies that need to be considered for energy minimization are detailed in the following pages. The reader will be led through a series of tables to help narrow down best strategies for meeting energy-minimization objectives. Table 3.2 provides an overview of the energy-minimization strategies that need to be considered for a selected application process. These components include

- System design and process optimization
- Pumping efficiency
- Selection of ERDs for desalination processes
- Selection of membranes for pretreatment and desalination
- Selection and optimization of advanced oxidation processes for AWT
- Selection of nonprocess heating, ventilation, and air conditioning (HVAC) and lighting

All energy-minimization strategy components are impacted during the design phase and should be considered during the project conceptual stage.

For seawater and brackish water desalination, energy minimization is achieved by proper system design, efficient pumping, utilization of ERDs, selection of membranes, and efficient utilization of nonprocess components.

AWT typically consists of MF/UF membranes followed by RO and UV/hydrogen peroxide. Advanced water treatment can also utilize a membrane bioreactor (MBR) treating raw wastewater or primary effluent, followed by RO and UV/hydrogen peroxide. For AWT technologies, maximum energy efficiency is obtained through system design/process modification and efficient pumping. For AWT technologies involving membranes (MF/UF, MBR), proper selection of membranes also reduces energy. Strategies that need to be

considered for energy minimization are detailed in the following pages. Each of the strategy components listed in Table 3-2 is elaborated on in the following subsections, which will help readers narrow down the best strategy options for meeting their energy-minimization objectives.

3.3.1 System Design and Process Optimization

System design and process optimization component parameters for energy-efficient operations are provided in the following subsections.

3.3.3.1 Seawater Desalination System Design and Process Optimization Strategies

System and process optimization strategies for energy-efficient operation of specific parameters during seawater desalination are listed in Table 3.3. A general discussion of enhanced RO system design covering staging, passes, high-efficiency pumping, energy recovery, advanced membrane materials, and the application of innovative technologies is provided in Appendix B, Section 5.

Fouling of membrane elements results in higher feed pressure requirements for the same operational flux. Thus, selection of the optimum membrane flux results in reduced fouling and operating pressures. Selection of the optimum number of membrane stages and passes is dependent on the treated water quality that is desired. Single-stage design results in lesser pressure drop across the system, resulting in a lower feed pressure requirement than for a two-stage or multistage design. Selection of a single-pass or multipass system should be based on the treated water quality that is desired. For higher rejection of specific compounds in seawater, such as boron, a multipass design is essential. Co-location of the desalination plant with a power plant results in the utilization of warmer feed water, which eventually results in a lower feed pressure requirement for the RO membranes. Detailed descriptions of energy minimization through system design are provided in Section 5.3.1 of Appendix B.

Table 3.2. Energy-Minimization Strategy Components That Need to Be Considered for Specific Application Processes

Application Process	System Design/Process Optimization	Pumping	ERD	Membranes	Nonprocess
		Desalination			
Seawater	✓	✓	✓	✓	✓
Brackish water	✓	✓	✓	✓	✓
		AWT			
MF/UF	✓	✓		✓	✓
MBR	✓	✓		✓	✓
UV	✓	✓			✓
Ozone	✓	✓			✓

Table 3.3. Strategies for Efficient System Design and Process Optimization for Seawater RO Desalination (Wilf and Bartels, 2005; Zhu et al., 2009; Voutchkov, 2004; Data Obtained from Utility Survey)

Parameter	Energy Efficiency Strategy for RO Systems—Seawater Desalination	Outcome
Membrane flux	Selection of the best membrane flux based on feed water quality.	Reduced membrane fouling and operating pressures.
Array configuration	Determination of the optimum combination of RO membrane element, array, stages and passes.	Reduced energy consumption due to reduced membrane feed pressure.
Number of stages	Utilization of single-stage design when applicable with seven or eight elements in a pressure vessel.	Reduced energy consumption compared to two-stage design because of lower pressure drop across RO trains. Up to 2.5% lower power requirement.
Number of passes	Utilization of first-pass front-end element permeate as feed to second pass. Utilization of membranes with highest salt rejection in the first pass.	Reduced feed pressure requirement for second pass.
Process control system	Utilization of energy-optimal set points for controlling concentrate valve position and feed flow rate.	Ability to achieve energy-optimal operation of RO system close to theoretically predicted energy consumption curves.
Process performance monitoring	Monitoring and recording of operating data to monitor process performance.	Reduced energy consumption due to lower feed pressure requirement as a result of early fouling detection.
Co-location	Co-location of desalination plant with existing power plant.	Reduced energy consumption by utilizing warmer water discharged from condensers in power plant. Up to 5–8% lower feed pressure requirement .

3.3.1.2 Brackish Water Desalination System Design and Process Optimization Strategies

System and process optimization strategies for energy-efficient operation during brackish water desalination are listed in Table 3.4. Similarly to seawater desalination, system design and process optimization strategies are based on the selection of optimum flux, array design, process control monitoring, and process control. In addition, utilization of new types of pressure vessels results in lower energy consumption. Detailed descriptions of energy minimization through system design are provided in Section 5.3.1 of Appendix B.

Table 3.4. Strategies for Efficient System Design and Process Optimization for Brackish Water RO Desalination (Zhu et al., 2009; Wilf and Hudkins, 2010; Data Obtained from Utility Survey)

Parameter	Energy Efficiency Strategy for RO Systems—Brackish Water Desalination	Outcome
Membrane flux	Selection of the best membrane flux based on the feed water quality.	Reduced membrane fouling and operating pressures that result in lower energy consumption.
Array design	Determination of the optimum combination of RO membrane element, array, stages, and passes.	Reduced energy consumption due to reduced membrane feed pressure.
RO pressure vessel design	Utilization of center port design for element instead of side port design.	Reduced energy consumption due to reduced feed pressure requirement as a result of reduced flow path within pressure vessel. Up to 15% reduction in feed pressure requirement.
Process performance monitoring	Monitoring and recording of operating data to monitor process performance.	Reduced energy consumption due to lower feed pressure requirement as a result of early fouling detection.
Process control system	Utilization of energy-optimal set points for controlling concentrate valve position and feed flow rate.	Ability to achieve energy-optimal operation of RO system close to theoretically predicted energy consumption curves.

3.3.1.3 Advanced Water Treatment System Design and Process Optimization Strategies

MF/UF Systems

System and process optimization strategies for energy-efficient operation of MF/UF membranes are listed in Table 3.5. For MF/UF systems, maximum energy efficiency is obtained from pretreatment, efficient operation of the pumps, and selection of the membrane. Selection of proper pretreatment for the MF/UF process will reduce the backwash frequency. Fouling of the MF/UF membranes leads to higher backwash and cleaning frequency. Higher backwash frequency will result in higher energy consumption as a result of associated pumping requirements. Heating the cleaning chemical solution also results in higher energy consumption. Further information on MF/UF systems is provided in Section 4.1 of Appendix B.

Table 3.5. Strategies for Efficient System Design and Process Optimization for MF/UF Processes

Parameter	Energy Efficiency Strategy for MF/UF	Outcome
Pretreatment	Selection of pretreatment to effectively reduce organic and particulate loading to membranes.	Decreased membrane fouling. Longer cleaning intervals.
Membrane flux	Selection of best membrane flux based on the feed water quality. Utilization of low-fouling membranes based on membrane surface chemistry.	Decreased membrane fouling. Longer cleaning intervals.
Backwash optimization	Utilization of optimized backwash and back pulse frequency.	Reduced energy requirements for pumping backwash water.
Air scour optimization	Restriction of air scouring when influent water quality is poor.	Reduced energy requirements from minimizing air scouring frequency.
Hydraulic loading	Operation of membrane trains based on feed flow rate. Shutdown of certain trains during low-flow conditions.	Optimized energy consumption from operation at highest pump efficiency.

MBR Systems

System and process optimization strategies for energy-efficient operation of MBR systems are listed in Table 3.6. MBRs are specialized applications of low-pressure membranes modified for municipal wastewater treatment. In an MBR process, a combination of low-pressure membrane filtration and the activated sludge process is involved. Further information on MBR is provided in Section 4.1 of Appendix B.

Selection of optimum fine screens upstream of the MBR process can minimize the sludging (plugging or fouling) of membrane fibers with fibrous materials. Primary clarification can also be utilized upstream of the MBR process to reduce organic loading. The primary sludge produced from the clarifiers can then be utilized for energy production if anaerobic digesters are utilized at the treatment plant.

In certain design configurations (with primary clarifiers), aeration basins can be designed for operation at lower mixed-liquor suspended solids (MLSS) concentrations. This mode of operation reduces the solids recycle flow by 50%, reducing energy associated with pumping and oxygen transfer. This lower MLSS design may be limited, however, to sites where plant footprint area is not an issue, because this design and operating strategy will require a larger footprint area for the bioreactors.

When anaerobic digesters are available/utilized at the treatment plant, the biological treatment process can be designed with a lower sludge retention time (SRT) of 12–15 days depending on the water temperature. This design would ensure complete nitrification as well as minimizing process air consumption related to endogenous decay. Operation at lower SRT

would also result in higher secondary sludge production, which can then be utilized for energy production through anaerobic digestion and use of the biogas produced.

Additional Resources

Design considerations for MBR systems:
http://www.gewater.com/products/equipment/mf_uf_mbr/mbr/design_considerations.jsp.
Last accessed: July 12, 2011.

Table 3.6. Strategies for Efficient System Design and Process Optimization for MBR Processes (Hribljan, 2007; Chang et al., 2008; Wallis-Lage and Levesque, 2011)

Parameter	Energy Efficiency Strategy for MBR	Outcome
Pretreatment	Selection of pretreatment to effectively reduce organic loading to membranes.	Decreased membrane fouling. Longer cleaning intervals. Reduced process aeration requirements.
Balance of solids	Operation at lower MLSS when using large aeration basin.	Reduced solids recycle flow rate. Reduced pumping energy and aeration.
Air scour optimization	Application of intermittent/cyclic air scouring.	Reduced energy requirements in membrane tank.
Aeration	Utilization of fine-bubble diffusers.	Optimized oxygen transfer efficiency. Reduced aeration energy.
Blowers	Utilization of single-stage, multistage, or turbo blowers.	Maximized energy efficiency.

Table 3.7. Strategies for Efficient System Design and Process Optimization for UV and AOP (Chang et al., 2008)

Parameter	Energy Efficiency Strategy for UV Systems	Outcome
UV dose control, oxidant dose control, and monitoring	Adjustment of lamp power based on flow rate, level of treatment (dose), and water quality (UV transmittance). For AOP process using oxidant and UV, control the oxidant dose and residuals required.	Reduced energy consumption during lower flow rate, lower level of treatment, and higher UV transmittance conditions. Reduced chemical consumption for oxidant due to optimization of applied dose which has an overall GHG emissions reduction when considering reduced chemical usage.
UV contactor	Selection of the UV contactor with lowest energy consumption, hydraulic head loss and pumping requirement.	Reduced energy consumption due to lower electricity requirements for the UV lamps and reduced pumping requirements from lower hydraulic head loss.
Lamp configuration	Selection of the best lamp configuration to avoid UV emission losses due to self-absorption, refraction.	Reduced energy consumption due to transmission losses.

UV Systems

System and process optimization strategies for energy-efficient operation of UV systems are listed in Table 3.7. For UV systems, dose control and selection of UV type and configuration will result in the lowest energy consumption. Additional information on UV systems is provided in Section 4.2 of Appendix B.

Additional Resources

UV system information and case studies:
http://www.trojanuv.com/uvresources. Last accessed: July 12, 2011.
http://www.calgoncarbon.com/uv/disinfection.html. Last accessed: July 12, 2011.
http://www.freshwatersystems.com/c-157-uv-systems.aspx. Last accessed: July 12, 2011.

Table 3.8. Strategies for Efficient System Design and Process Optimization for Ozonation Processes (Chang et al., 2008)

Parameter	Energy Efficiency Strategy for UV Systems	Outcome
Dose control	Adjustment of ozone dosage based on flow rate, level of treatment, and water quality.	Reduced energy consumption during lower flow rate, lower level of treatment, and better water quality.
Ozone generator and dielectrics	Selection of the number and size of ozone generator units to match expected water flow and dose range for operation at best efficiency point. Optimization of ozone generator cooling water flow and system to maximize the ozone generator efficiency.	Reduced energy by implementing these energy efficiency strategies.
Ozone diffusers and contactor	Selection of ozone gas diffusers that provide the most efficient transfer of gas into the water to achieve required dose. Design and selection of ozone off-gas destruct system for energy efficiency.	Reduced energy consumption by utilization of efficient ozone diffusers and contactor design to maximize the ozone transfer efficiency.
Air and oxygen enrichment compressor design	Utilization of smaller compressors.	Reduced energy consumption by utilization of low oxygen production rates.

Ozone Systems

System and process optimization strategies for energy-efficient operation of ozone systems are listed in Table 3.8. For ozonation systems, maximum energy minimization is obtained from dose control and efficient system design for ozone generators and compressors. Additional information on ozonation systems is provided in Section 4.3 of Appendix B.

Additional Resources

Ozone information:
http://www.degremont-technologies.com/dgtech.php?rubrique68. Last accessed: July 12, 2011.

3.3.2 Pumping Strategies for Energy Efficiency

Pumping strategies for energy efficiency are common to desalination and AWT processes. Pumping energy is predominantly consumed in operation of pretreatment pumps, feed pumps to the system, product water transfer pumps, chemical feed pumps, and water distribution pumps. Pumps and motors have significant energy demand, capital investment, and maintenance requirement. Proper selection and maintenance will reduce energy costs and improve reliability. Additional information on high-efficiency pumping is provided in Section 5.3.2 of Appendix B.

The following strategies should be considered to obtain the highest possible pumping efficiency:

Sizing pump and motor equipment

- Size pumps based on the intended flow rate. Operating pumps at lower than design capacity leads to higher energy consumption. Pumps should be operated at or near their best efficiency point (BEP).
- Utilize large pumps with a centralized design to feed several trains of treatment processes instead of using several pumps to feed treatment processes.
- To size down pump capacity, replace the pump and motor with a downsized model, replace the impeller with a lower-capacity one, trim the outside diameter of the existing impellers, install a variable-frequency drive (VFD) to control load requirements, and add a smaller pump to reduce intermittent operation of a larger existing pump.

Verifying energy-efficient operation of pumps and motors

- Energy efficiency of existing pumps and motors should be verified every 3 months.
- Motor efficiency can be maintained by periodic monitoring of ventilation and temperature control required for optimal operating conditions as provided by manufacturer.
- Replacement of inefficient motors with higher-efficiency motors is an effective method for improvement in energy reduction.

Typical information needed while choosing pumps and considering maintenance is listed in Table 3.9. Following a maintenance schedule will result in improved energy efficiency. An example of energy efficiency obtained by replacing older pumps and motors with newer ones for a large-scale AWT plant is shown in Table 3.10.

Table 3.9. Considerations for Pump Design and Efficient Maintenance Strategies

Required Equipment Information	Conditions to Consider
Pump style	Flow rate (capacity) fluctuations
Manufacturer pump curves	Replacement of bearing and seals
Actual (operating) pump curves	Lubrication
Pump stages required	Cavitation on pumps, impellers, and bearing
Pump rated head	Out-of-alignment conditions
Pump and motor speed	Excessive noise or vibrations
Full load current requirement (A)	Significant flow rate and pressure fluctuations
Rated and actual (operating) pump discharge	Leaks
Operating schedule	Replacement of older, less efficient motors
Constant speed or variable speed	Benefits of variable-speed drive and pumping operation

Table 3.10. Improvement in Energy Efficiency from Replacing Older Pumps with Newer Pumps (Data Obtained from Utility Survey)

Pump	Existing Efficiency, %	Improved Efficiency, %
Hot water pump	37	59
Cold water pump	48	59
MF Feed Pump	36	65
MF Filtrate Pump	50	63
RO Feed Pump	59	70
RO Transfer Pump	63	70

Utilization of Variable Frequency Drives (VFDs)

- VFDs have a soft start, allow precise control of motors and processes, enhance the efficiency of motors, and significantly reduce energy demand.
- VFDs can be used to eliminate over pumping during product water feed and transfer operations.
- VFDs can be used to accommodate the variability in feed pressure with time without the necessity to throttle high-pressure pumps or ERDs. This variability may be due to feed water salinity changes, temperature change, RO membrane fouling, and RO membrane age.

Additional information on VFDs is provided in Section 5.3.2 of Appendix B.

Additional Resources

Pump System Assessment Tool (PSAT):
http://www1.eere.energy.gov/industry/bestpractices/software_psat.html. Last accessed: July 12, 2011.

> PSAT is a free online software tool to help utility users assess the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings. The tool also enables users to save and retrieve log files, default values, and system curves for sharing analyses with other users. The software can be accessed using the PSAT web link.

Pump System Improvement Modeling Tool (PSIM):
http://www.pumpsystemsmatter.org/content_detail.aspx?id=110. Last accessed: July 12, 2011.

> PSIM is a free educational tool focused on helping you better understand the hydraulic behavior of pumping systems. With the challenges of today's marketplace, your fluid handling systems must be both cost effective and energy efficient. It is essential that users evaluate the total pump system in their designs.

Estimation of electric motor load and efficiency:
http://www1.eere.energy.gov/industry/bestpractices/pdfs/10097517.pdf. Last accessed: July 12, 2011.

> Methods for estimating electric motor load and efficiency are provided by a document from the Department of Energy.

Motor Systems Initiative tool kit:
http://www.cee1.org/ind/mot-sys/mot-sys-tools.php3. Last accessed: July 12, 2011.

> The Motor Systems Initiative has developed a tool kit to help motor program representatives and contractors promote a variety of motor-related efficiency improvements. The tool kit includes both technical tools (software, checklists, guidelines, etc.) and promotional tools targeting the interests of a variety of audiences, such as maintenance, operation, and management personnel.

Department of Energy (USDOE) Motor Challenges Program:
http://www1.eere.energy.gov/industry/bestpractices/techpubs_motors.html. Last accessed: July 12, 2011.

> Guidance documents on technology, economics and maintenance and repair of motors can be found in the USDOE web link.

California Public Utilities Commission:
http://www.cpuc.ca.gov/PUC/Water/oeep/. Last accessed: July 21, 2011.

> Guidance documents on the water–energy nexus and the Operational Energy Efficiency Program (OEEP) for efficient pump design and operation for energy minimization.

3.3.3 Selection of Energy Recovery Devices

Recovery of energy is crucial in making desalination of high-salinity water economically feasible. Utilization of ERDs can reduce energy consumption up to 30% for seawater desalination. For brackish water desalination, ERDs are used as interstage (in between first- and second-stage) booster pumps. Thus, the feed pressure requirement of the feed pump (in front of the first stage) is reduced, thereby reducing overall energy consumption. The fraction of energy recovered depends on the type and efficiency of the equipment used. Comparison of ERDs and a thorough discussion of each type of ERD is provided in Section 5.3.3 of Appendix B.

Additional Resources

Pressure and work exchanger:
http://www.energyrecovery.com/index.cfm/0/0/33-Overview.html. Last accessed: July 12, 2011.
http://www.flowserve.com/Products/Energy-Recovery-Devices/Work-Exchangers. Last accessed: July 12, 2011.

Turbines:
http://www.flowserve.com/Products/Energy-Recovery-Devices/Turbines. Last accessed: July 12, 2011.
http://www.fedco-usa.com/prod_products_high.html. Last accessed: July 12, 2011.
http://www.fedco-usa.com/prod_products_low.html. Last accessed: July 12, 2011.

White Papers and ERD implementation:
http://www.energyrecovery.com/index.cfm/0/0/55-White-Papers.html. Last accessed: July 12, 2011.
http://www.flowserve.com/Services-and-Solutions/Engineering-and-Technical-Services. Last accessed: July 12, 2011.
http://www.fedco-usa.com/techpapers_main.html. Last accessed: July 12, 2011.
http://www.fedco-usa.com/comparisons_main.html. Last accessed: July 12, 2011.

Table 3.11. Strategies for Efficient System Design and Process Optimization for Desalination Using Different Membrane Types and Configurations (Subramani et al., 2011)

Parameter	Energy Efficiency Strategy for RO Systems—Membrane Type and Configurations	Outcome
Combination of brackish water RO–seawater RO elements	Utilization of high-rejection brackish water RO elements (or) high-permeability seawater RO elements in the first stage. Second stage consisting of standard seawater RO elements.	Reduced energy consumption by 5%.
Combination of RO or NF membranes in array	Utilization of computer models to determine feed pressure reduction when a combination of NF and RO membranes are used within a single array or pressure vessel.	Reduced energy consumption.
Two-pass nanofiltration	Utilization of nanofiltration membranes in a two–pass configuration.	Reduced energy consumption by 12%.

3.3.4 Selection of Membranes

Selection of membrane type can reduce energy consumption during desalination by reducing the feed pressure requirement. Parameters that need to be considered for proper selection of membranes to reduce energy consumption are listed in Table 3.11. Utilization of a combination of brackish water and seawater RO elements within a pressure vessel is an established method. Utilization of novel membrane materials (nanocomposites, carbon nanotubes, biomimetics) and innovative processes (such as forward osmosis) shows promise for reducing energy consumption, but limited data are currently available on these novel materials and technologies. Additional information on new-generation membrane types that can reduce energy consumption is provided in Section 5.3.4 of Appendix B.

Additional Resources

Two-pass nanofiltration:
http://www.lbwater.org/pdf/desal_lbmethod.pdf. Last accessed: July 12, 2011.
http://www.lbwater.org/pdf/desalination/desalination_test_plan.pdf. Last accessed: July 12, 2011.

Nanocomposite membranes:
http://www.nanoh2o.com/Technology.php5. Last accessed: July 12, 2011.

Carbon nanotube membranes:
http://www.poriferanano.com/our-technology.html. Last accessed: July 12, 2011.
http://www.nanoasisinc.fogcitydesign.com/news.html. Last accessed: December 14, 2011.

Biomimetic membranes:
http://aquaz.dk/aquaporin_membrane_technology.asp. Last accessed: July 12, 2011.

Forward osmosis:
http://www.yale.edu/env/elimelech/News_Page/files/membrane_technology_jan2007.pdf. Last accessed: July 12, 2011.
http://www.htiwater.com/technology/forward_osmosis/index.html. Last accessed: July 12, 2011.
http://www.technologyreview.com/energy/26916/. Last accessed: July 12, 2011.
http://www.filtsep.com/view/18901/modern-water-to-build-first-commercial-forward-osmosis-desalination-plant/. Last accessed: December 14, 2011.

3.3.5 Selection of Nonprocess Heating, Ventilation, and Air Conditioning and Lighting

Strategies for efficient design and maintenance of HVAC and lighting systems are listed in Table 3.12. Utilization of newer HVAC and lighting systems can reduce building energy use by 10–40%. Implementation of programmable thermostats, prevention of AC loss, regular maintenance of air filters, use of energy-efficient lamps, and motion sensors can substantially reduce building HVAC energy consumption.

Table 3.12. Strategies for efficient design and maintenance of HVAC and lighting systems.

HVAC	Lighting
Alter settings of system seasonally	Installation of occupancy sensors
Installation of high efficiency equipment	Replacement of incandescent lights with fluorescent systems
Utilization of programmable thermostats	Replacement of older lighting with energy efficient lamps
Prevention of solar entry and AC loss	
Regular cleaning of air filters	

Additional Resources

Energy-efficient technologies in your buildings:
http://www1.eere.energy.gov/calculators/buildings.html. Last accessed: July 12, 2011.
http://www.energystar.gov/index.cfm?c=tools_resources.bus_energy_management_tools_resources. Last accessed: July 12, 2011.

Chapter 4

Utilization of Renewable Energy Resources

In this chapter, various renewable energy resources and parameters that need to be considered for implementation in desalination and water reuse are reviewed. The chapter provides steps required for developing renewable energy resource utilization and a discussion of various technologies available, financing options, and design considerations. Components involved in renewable energy utilization on a large scale are shown in Figure 4.1. Additional information on renewable energy resources is provided in Appendix C.

Understand the benefits and challenges of renewable energy resource implementation.

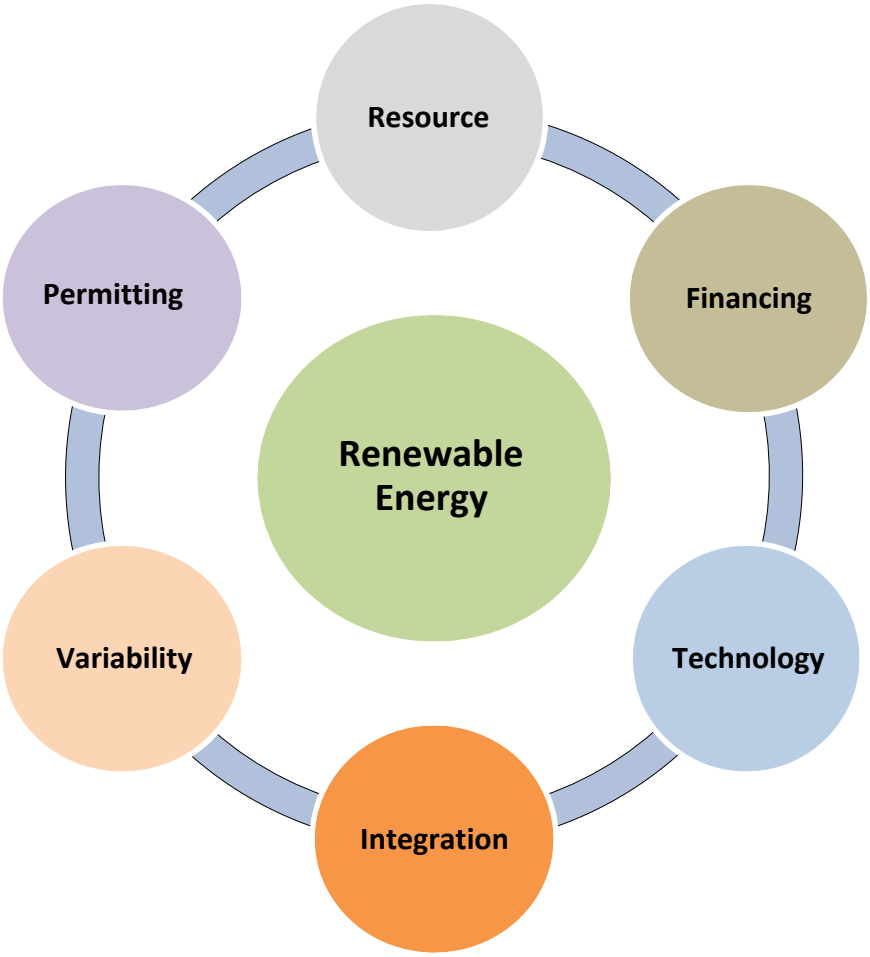


Figure 4.1. Components involved in renewable energy utilization on a large scale.

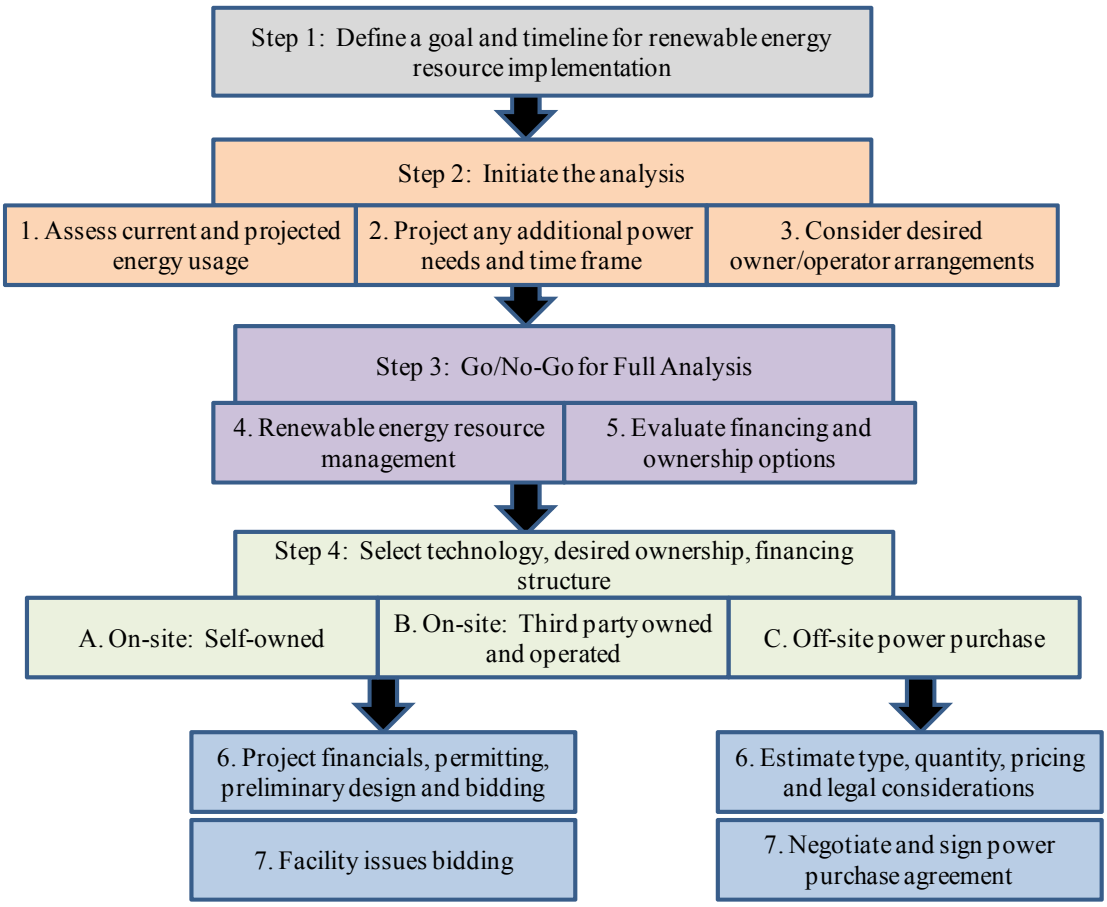


Figure 4.2. Typical process for developing a renewable energy project.

4.1 Steps in Renewable Energy Resource Implementation

Utilization of renewable energy is a stepwise process. Typical components involved in implementing renewable energy resources are shown in Figure 4.2.

Step 1

The first step is to define a goal for implementation of renewable energy to supply partial or complete power requirements. It will also be necessary to define a timeline for implementation of renewable energy resource utilization.

Step 2

The second step is to assess current and projected energy usage, current and projected future energy costs, and desired characteristics of a renewable energy system. Details of assessing current and project energy usage should include the following:

- Facilities must first understand their total annual energy consumption, the make-up of that power mix (e.g., is the facility already paying for renewables as part of the power utility's mix?), and the current cost of that power.

- Then projections must be made to understand any additional power needs and the anticipated time frame, as well as the anticipated cost escalations of grid-provided power.
- Finally, a critical step is to understand the characteristics or goals of desired renewable energy purchases. For example:
    - Does the facility wish to provide visible proof of its environmental stewardship? If so, an on-site renewable project may be desirable.
    - Does the facility wish to incentivize cutting-edge renewable technologies? If so, a less proven technology might be desirable.
    - Does the facility wish to be energy- or carbon-neutral? If so, minimally a mix of off- and on-site renewable energy should be considered.
    - Does the facility have cost as the principal driver? If so, the financial options that capture the greatest incentives, and possibilities such as purchasing renewable energy from large-scale off-site projects, may be more desirable.
    - Does the facility wish to avoid owning and operating the renewable energy assets? If the facility wishes to own and operate renewable energy assets, on-site leasing of land, seeking renewable power purchase agreements, and procuring and training its own operators may be considered.

DECISION POINT 1: A facility should decide whether or not to contract with an outside entity to provide a basic pre-feasibility study of renewable energy options. The remaining steps can be self-performed or contracted out.

Step 3

The third step is to understand renewable energy resource availability and financing options. Details for assessing renewable energy resources and finance should include the following:

- Assess the availability of on-site land or surface area (roofs, concrete tank tops) for renewable energy locations and the desirability of each location for this purpose.
- Assess resources, because renewable energy availability depends on the location. Estimate availability using resource maps, on-site surveys, and available software. For biomass energy, a regional survey of available sources within affordable driving range (typically 50 miles) will be necessary, as well as a comparison of pricing for alternative uses of that biomass.
- Assess options for off-site energy. Unless additional off-site land is already owned by the plant, this option typically would involve the purchase or lease of land, as well as the construction of associated infrastructure (primarily the grid interconnect), and finally, the wheeling of power from the local electrical grid. When this option is considered, it is typical to contract with a third party for the full ownership, operation, and wheeling of power. The plant owner may purchase part or all of the power that is generated through a power purchase agreement with that provider.
- Initial investment of renewable energy can be substantial.
- Funding options available from renewable energy providers and incentives from state and federal government need to be considered for a renewable energy project. However, many of these incentives are available to tax-paying entities only. Thus, the ownership of the renewable energy—public or private—may significantly impact the financial viability of the project.

- Two broad financing options are typically taken by a facility owner for the addition of renewable energy:
  - Self-owned: The utility owns the renewable energy technology and the associated components for power generation. However, if the facility owner is a public entity, this option may be more expensive.
  - Third-party owned: The power is purchased by the utility through a power purchase agreement. This option might be for a facility located either on or off site. This option does not necessarily require a new renewable plant to be constructed; a utility might decide to buy excess capacity from an existing renewable energy plant, or an already planned renewable energy plant. This option can allow for cost benefits (1) through the ability of the private party to claim state and federal incentives, and (2) through the economies of scale of a larger off-site project.

DECISION POINT 2: Based on the resource assessment and financing options available, a facility should decide at this point whether or not to initiate a full analysis for renewable energy utilization.

Step 4

The fourth step is to select a technology, type of ownership, and financing structure.

- Based on the resource availability and funding options available, select a renewable energy technology that is available commercially and well proven.
- While selecting a technology, determine footprint requirements to accommodate the renewable energy technology (if on site).
- Based on decisions made earlier, select the ownership and financing structure desired. If the utility decides to own and operate the facility itself, it will then need to determine and implement the staffing requirements to do so. Hire or continue the services of a contractor, who will work with the utility's project manager to
  - Estimate the infrastructure requirement for the technology selected, the physical footprint required, and the type of integration (on-site grid or off-site grid connected). Calculate the budget and ROI.
  - Determine the total capital and operation and maintenance (O&M) cost of the project.
  - Estimate ROI on funding options available.
  - Determine tariffs, regulations, and permits.
- Identify regulations and permitting requirements based on the location of the plant.
- Develop preliminary design sufficient for bid and prepare bid documents.

DECISION POINT 3: Utility issues bid for engineering, procurement, construction, ownership, and operation with the intent to own and operate the facility itself or utilize third-party ownership. After negotiation of the type of financing structure, the facility issues bidding for construction of the project

4.2 Resource Availability

Renewable Energy Resource Maps

Selection of the best renewable energy resource varies with location. Determine renewable energy resource availability by utilizing resource maps**.**

Renewable energy resource maps are readily available at the National Renewable Energy Laboratory (NREL) Web site. Web links to resource maps are provided in the Additional Resources section. The resource maps can be utilized to determine renewable energy potential based on the location of the utility in the United States.

Additional Resources

Solar radiation resource map:
http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/. Last accessed: July 12, 2011.

Wind energy resource map:
http://www.windpoweringamerica.gov/wind_maps.asp. Last accessed: July 12, 2011.

Photovoltaic solar resource map:
http://www.nrel.gov/gis/solar.html. Last accessed: July 12, 2011.

Concentrating solar power resource map:
http://www.nrel.gov/gis/solar.html. Last accessed: July 12, 2011.

Wind energy resource map:
http://www.nrel.gov/gis/wind.html. Last accessed: July 12, 2011.

Geothermal energy resource map:
http://www.nrel.gov/gis/images/geothermal_resource2009-final.jpg. Last accessed: July 12, 2011.

4.3 Financing and Incentives

Utilities have several options for procuring renewable energy systems. They can choose to purchase the equipment up front, using conventional financing options such as municipal leases. Financing options and incentives available for utilities to implement renewable energy are described in this section. Additional information on cost of renewable energy resources is provided in Section 2.11 and Section 2.12 of Appendix C.

1. *Clean Renewable Energy Bond (CREB) Program:* Local governments, electric cooperatives, and municipal utilities can issue bonds and repay only the principal. The lender receives a tax credit instead of the traditional interest. Available since 2008.
   - The amount of bonds allocated is limited and an application has to be filed with the IRS to receive an allocation. The IRS requires significant time to authorize, structure, price, and close the application.
   - CREB remains one of the cheapest sources of debt financing.

2. *Performance Contracting:* Allows utilities to fund renewable energy facilities through loan or lease arrangements. Typically performance contracting is used for energy conservation measures, but it can also be used with renewable energy installations. A long-term (10–25 years) contractual agreement is established between the contractor and the utility agreeing to the terms of performance.
   - All aspects of financing are provided by a qualified third-party financial institution.
   - A contractual agreement is entered into by the contractor and the utility, agreeing to the terms of performance. Typically this involves the utility agreeing to pay a price per kWh with future escalation clauses, and the contractor guaranteeing a certain level of performance with penalty clauses for any shortfalls.
   - The utility uses operating funds (the appropriated maintenance and energy budget) to pay back the capital improvement and associated costs. Any excess savings are usually retained by the utility.
   - After the contract performance period, all associated savings are transferred to the utility. System ownership will be defined by the financial arrangement and defined in the contractual agreement.
   - Any capital provided up front by the utility can help shorten the length of the contract and improve terms for the utility.
   - The utility owns the Renewable Energy Credits/Certificates (RECs) generated from on-site renewable energy implementation, and the utility may sell the credits on the open market.
3. *Third-Party Ownership with a Power Purchase Agreement:* Provides utilities with the ability to utilize benefits for renewable energy through service contracts while avoiding the risks associated with direct ownership.
   - The utility enters into a contract with the vendor, typically known as an independent power provider (IPP), to have it install a renewable energy system and deliver a set amount of power at an agreed price. This is known as a power purchase agreement (PPA). Typically PPAs have a number of contractual elements, and unless PPA contractual expertise is available within the utility, the services of a neutral power consultant may be desirable to negotiate these on good terms for the utility.
   - The renewable energy equipment provider enters into an agreement with a financial institution and then engineers, procures, and constructs the plant.
   - The renewable energy plant may be located either on or off site, depending upon the amount of power desired, the availability of land and the energy resource, the most attractive location for associated infrastructure, permitting, and the total financial implications. For on-site energy, a land lease agreement with the IPP may be needed.
   - Because municipal utilities may not claim many of the available federal and state incentives, the vendor providing the renewable energy system can claim incentives. This option typically results in a lower total cost per kWh.
   - The third party (vendor providing the renewable energy system) is responsible for operating and maintaining the on-site renewable energy facility.
4. *Financial Incentives:* Financial incentives for renewable energy provide small incremental benefits that help reduce the total cost of a project over its life cycle. These may include renewable energy credits, net metering, state public benefit funds, state clean energy funds, utility rebate programs, federal investment tax credits, grants in lieu of tax credits, state grants, and accelerated depreciation.

5. *Renewable Energy Credits/Certificates:* RECs come from the adoption of renewable energy portfolio standards (RPS) set by individual states and represent nonpower attributes of 1 MWh generated from a qualifying energy source. RECs can be traded to help electric utilities reach the generating goals imposed under RPS. In states with open REC markets, a REC is priced at the difference between the utility power rate and the actual cost of generation from a renewable energy source, making them competitive with conventional power sources.
6. *Investment Tax Credit:* Business energy investment tax credit (ITC) provides corporate tax credits, as a percentage of total expenditures, for the installation of new solar (thermal and electric), wind, biomass, and geothermal (thermal and electric) energy, fuel cells, solar hybrid lighting, and microturbines. The credit amount varies by technology and is subject to certain caps.
7. *Renewable Energy Production Incentives:* Renewable energy production incentive (REPI) complements the ITC and provides direct revenue to the generating entity based on performance. Qualifying new renewable energy installation received 2.2 cents/kWh in 2011 for the first 10 years of system operation.

Direct financial incentives are more volatile, depending on yearly appropriations, and can vary significantly with time. The utility should always check availability and eligibility of financial incentives, as they could have a significant impact on the economics of the project.

Additional Resources

Database of State Incentives for Renewables and Efficiency (DSIRE):
http://www.dsireusa.org/Index.cfm?EE=0&re=1. Last accessed: July 12, 2011.

> DSIRE is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency. Established in 1995 and funded by the U.S. Department of Energy, DSIRE is an ongoing project of the N.C. Solar Center and the Interstate Renewable Energy Council.

USDOE Loan Guarantee Program:
http://lpo.energy.gov/. Last accessed: July 12, 2011.

Energy savings performance contracts:
http://www1.eere.energy.gov/femp/financing/espcs.html. Last accessed: April 5, 2012.

> Energy savings performance contracts (ESPCs) allow Federal agencies to accomplish energy savings projects without up-front capital costs and without special Congressional appropriations.

Types of financing programs:
http://www1.eere.energy.gov/wip/solutioncenter/financialproducts/financingprograms.html. Last accessed: July 12, 2011.
http://www.energystar.gov/index.cfm?c=business.EPA_BUM_CH4_Financing. Last accessed: July 12, 2011.

Information on various types of financing programs, such as state and municipal revolving loan funds, third party loans, energy savings performance contracts (ESPC), property-assessed clean energy (PACE), on-bill repayment, energy-efficient mortgages, power purchase agreement, FHA power saver, and qualified energy conservation bonds (QECBs) can be found at these web links.

Performance contracting:
http://www.energystar.gov/ia/partners/spp_res/Introduction_to_Performance_Contracting.pd. Last accessed: July 12, 2011.

Innovative financing solutions:
http://www.energystar.gov/ia/business/COO-CFO_Paper_final.pdf. Last accessed: July 12, 2011.

4.4 Technology

4.4.1 Commercial Technologies

4.4.1.1 Solar Photovoltaics

Principle

The solar photovoltaic (PV) process converts sunlight directly into electricity. A PV cell consists of two or more thin layers of semiconducting material. When the semiconducting material is exposed to sunlight, electrical charges are generated and this can be conducted away by metal contacts as direct current (DC). An inverter is used to convert DC to alternating current (AC). The amount of energy produced by a panel depends on several factors. These include the type of collector, the tilt and azimuth of the collector, the temperature, and the level of sunlight and weather conditions. Additional information on solar PV is provided in Section 2.2 of Appendix C.

System Components

- PV arrays, which convert light energy to DC electricity
- Inverters, which convert DC to AC and perform important safety, monitoring, and control functions
- Various wiring, mounting hardware, and combiner boxes
- Monitoring equipment

Types of Cells

- Photovoltaic cells can be either monocrystalline silicon cells, polycrystalline silicon cells, or amorphous (thin film) cells.
- Monocrystalline cells are made of very pure monocrystalline silicon, whereas polycrystalline cells are produced using numerous monocrystalline grains. Thin films are made by spreading amorphous silicon on large plates.

- Polycrystalline cells are the least expensive and are the most common type of cell used currently. Monocrystalline cells are favorable for large projects because of their higher energy yield, but this option is the most expensive. Thin films are less costly but are also less efficient, resulting in larger panels for the same power production.
- Thin film amorphous silicon is less expensive but is the least efficient when compared to CIGS (copper indium gallium selenide). Thin film CdTe (cadmium telluride) is considered less expensive than thin film silicon PV cells for multi-kilo watt systems..
- Concentrating PV adds lenses to concentrate light over solar cells.
- Typical area required by cells for 1 kW electricity generation is 10-14 square meter for monocrystalline and polycrystalline cells and 16-23 square meter for thin film cells (AEE, 2010).

Types of PV Systems

The electrical output from a single cell is small. Hence, multiple cells are connected together and encapsulated in glass to form a module or panel. The PV panel is the principal building block of a PV system, and any number of panels can be connected together to give a desired electrical output. Typical design parameters for solar PV systems are listed in Table 4.1. PV systems can be either ground-mounted or roof-mounted. Important aspects of each of these two types of systems follow.

Ground-Mounted Systems

- Ground-mounted systems are the least expensive based on a $/DC-W basis.
- System can be installed using a fixed-tilt, single-axis, or dual-axis tracking system. Fixed-tilt systems are installed at a specified tilt and are fixed at that tilt for the life of the system.
- Single-axis tracking systems have a fixed tilt on one axis and a variable tilt on the other axis. The system is designed to follow the sun in its path through the sky.

Table 4.1. Design Parameters for Solar PV Modules

Parameter	Description
Cell efficiency	Percentage of solar energy falling on PV cells that is converted into electrical energy
Module efficiency	Combination of cell efficiency placed into a module
Energy yield	Output in kilowatt hours (kWh) over time
Typical module size	175–200 W: 1 m × 1.5 m
Common types of modules	Polycrystalline, monocrystalline, amorphous silicon (thin film)
Module lifetime	Polycrystalline ~ 40 years; monocrystalline ~ 50 years; amorphous silicon ~ 20 years

- Single-axis tracking systems allow solar radiation to strike the panel at an optimum angle for a larger part of the day than for a fixed-tilt system.
- Single-axis tracking systems can collect up to 30% more electricity per capacity than fixed-tilt systems, but have higher O&M and installation costs.
- Dual-axis tracking systems allow tracking on two axes, thereby providing for both diurnal and seasonal shifts in the azimuth of the sun striking the earth. Though more expensive, these systems have the highest efficiencies.

Roof-Mounted Systems

- Roof-mounted systems are relatively more expensive than ground-mounted systems.
- Roof-mounted systems are more convenient because of less shading.
- In a roof-mounted system, a typical flush-mounted crystalline silicon panel can achieve power densities on the order of 1 DC-W/ m^2. For rack-mounted systems a power density of 0.8 DC-W/m^2 can be achieved (Lisell and Mosey, 2010).

Additional Resources

Solmetric solar path calculator:
http://www.solmetric.com/pvdesigner.html. Last accessed: July 12, 2011.

A Solmetric solar path calculator enables you to quickly and easily draw a roof outline, specify setbacks and keep-out regions, incorporate shade measurements at specific locations on a roof, use drag-and-drop modules, size strings, check inverter limits, and calculate the AC energy production for your system. It includes extensive world-wide databases of modules, inverters, and historical weather.

PVWATTS:
http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/. Last accessed: July 12, 2011.

PVWATTS is a performance calculator for grid-connected PV systems. PVWATTS can be used for locations accessible through links on the map provided in the web link, or through a text list for U.S. sites. or for sites outside the United States, through text lists by region. Researchers at the National Renewable Energy Laboratory developed PVWATTS to permit nonexperts to quickly obtain performance estimates for grid-connected PV systems.

Tools for renewable energy utilization:
http://www.energycommunity.org/default.asp?action=71. Last accessed: July 12, 2011.

4.4.1.2 Concentrating Solar Power (CSP) Systems

Principle

CSP systems are based on heating a heat-transfer fluid using mirrors, which is used to generate steam and run a turbine and generator to generate electricity. The main types of CSP are summarized in Table 4.2 and then described in more detail by type.

Table 4.2. Major Types of CSP Systems

Type	Description
Power tower	Mirrors are used to concentrate sunlight on top of a tower where molten salt is housed. The molten salt's heat is used to generate steam and run a turbine that drives a generator to produce electricity.
Linear concentrator	Long horizontal mirrored pipes are used to collect sunlight and focus it on a linear receiver tube containing oil. The heated oil is used to generate superheated steam, which is used to run a turbine that drives a generator to produce electricity.
Dish/engine system	A mirrored dish is used to heat fluid that expands a piston to produce mechanical power.

Types of Concentrating Solar Power (CSP) Systems

Three major types of CSP systems exist. They are power towers, linear concentrators, and dish/engine systems.

Power Tower

- A large field of flat sun-tracking mirrors (heliostats) are used to focus and concentrate sunlight onto a receiver on the top of a tall tower.
- A heat-transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine generator to produce electricity.
- Common heat-transfer fluids used are water and molten salt. When molten salt is used as the heat-transfer fluid, thermal storage is possible, allowing the system to generate electricity in cloudy weather and at night.

Linear Concentrator

- Long curved rectangular mirrors are used to focus sunlight on receiver tubes, which are used to heat a fluid (oil or molten salt) that in turn heats water and generates steam.
- The steam is used to generate electricity through a turbine and generator.
- Two major types of linear concentrators are parabolic trough and Fresnel reflector systems. In parabolic troughs, the receiver tubes are positioned along the focal line of each parabolic mirror. In Fresnel reflector systems, one receiver tube is positioned above several mirrors to allow the mirrors greater mobility in tracking the sun.
- Similarly to the power tower, when molten salt is used as the heat-transfer fluid, thermal storage is possible, allowing the system to generate electricity in cloudy weather and at night.

Dish/Engine System

- A dish/engine system uses a mirrored dish similar to a very large satellite dish.
- The dish-shaped surface directs and concentrates sunlight onto a thermal receiver, which absorbs and collects the heat and transfers it to the engine generator. The most common type of heat engine used today is a Stirling engine.

- The dish/Stirling engine system uses the fluid heated by the receiver to move pistons and create mechanical power. The mechanical power is then used to run a generator or alternator to produce electricity.

Additional Resources

Modeling tools for CSP systems:
http://www.nrel.gov/csp/troughnet/models_tools.html#dview. Last accessed: July 12, 2011.

The web link provides information about models and software tools used to analyze parabolic trough power plant technology. The tools provided are SolTrace, TRNSYS, Solar Advisor Model (SAM), Receiver Model, and JEDI.

Tool for estimating energy and environmental impacts of CSP:
http://www.nrel.gov/analysis/reeds/. Last accessed: July 12, 2011.

The Regional Energy Deployment System (ReEDS) model is a computer model that optimizes the regional expansion of electric generation and transmission capacity in the continental United States over the next 50 years. The web link presents an overview of this NREL-developed tool, as well as relevant data and related publications.

Concentrating Solar Power Research:
http://www.nrel.gov/csp. Last accessed: July 12, 2011.
http://www.nrel.gov/learning/re_csp.html. Last accessed: July 12, 2011.
http://www1.eere.energy.gov/solar/csp_program.html. Last accessed: July 12, 2011.
http://www.eere.energy.gov/basics/renewable_energy/csp.html. Last accessed: July 12, 2011.

TroughNet Parabolic Trough Solar Power Network:
http://www.nrel.gov/csp/troughnet. Last accessed: July 12, 2011.

TroughNet is a technical resource for evaluation of parabolic trough solar power plant technologies.

System and Component Testing:
http://www.nrel.gov/csp/troughnet/testing_standards_reports.html. Last accessed: July 12, 2011.

4.4.1.3 Wind Energy

Principle

Wind turbines convert the kinetic energy of the wind into electricity. The blades of a wind turbine capture the wind's kinetic energy to spin a rotor that is used to generate electricity. The power of the wind is a function of the density of air, the area of the wind mill blades, and the cube of wind speed. Additional information on utilization of wind energy is provided in Section 2.4 of Appendix C.

Components of Wind Turbines

The primary components of a wind turbine are the turbine, nacelle, and tower.

Turbine

- The wind turbine consists of two or three blades made of high-density wood, Plexiglas, or a composite material. The blades develop an imbalance between the lift and drag forces to capture the wind's energy.
- Turbine aerodynamics, material composition, and size are fundamental issues in wind power system design. Regardless of system size, turbine price ranges from 10 to 40% of the total system cost (NYSERDA, 2005).

Utility-Scale Turbine

- Corresponds to large turbines (900 kW to 2 MW per turbine). Intended to generate bulk energy for sale in power markets.
- Typically installed as large arrays. Turbines connected to utility electricity grid through a transformer. Most common form of wind energy generation in the United States.

Industrial-Scale Turbine

- Corresponds to medium-sized turbines (50 kW to 250 kW per turbine). Intended for remote off-grid operation along with diesel generation or load-side generation to reduce on-site demand for higher-cost grid power and to reduce peak loads.
- Direct sale of energy to utility grid may or may not be allowed under individual state laws and utility regulations.

Residential-Scale Turbine

- Corresponds to small turbines (400 W to 50 kW). Intended for remote power, battery charging, or net-metering-type generation.
- Small turbines can be used with solar photovoltaics, batteries, and inverters to provide constant power at remote locations where access to electrical grid power is limited.

Nacelle

- Nacelles house a gearbox, a generator, control electronics, and a yaw mechanism.
- The spinning rotor blades are coupled to a shaft and generator through a gearbox.
- An induction generator is the most widely used for commercial applications and supplies electricity to the grid.
- The control electronics is used to sense wind speed, wind direction, rotor (turbine) speed, and generator load. When wind speed changes, the control electronics adjusts rotor speed and blade pitch to maximize power capture. When wind speeds are too high, the control electronics depowers the turbine to avoid damage.

Tower

- The tower supports the blades and nacelle and withstands vibrations and cyclic stresses associated with wind. Towers for commercial large-scale installations range from 30 to 120 m in height.
- The tower also shelters the power line connections between the generator and the transformer and electricity grid.

Considerations for Wind Energy Utilization

Factors that need to be considered for wind energy utilization are discussed in this section.

- *Understand your wind resource by checking wind speed:* Annual average wind speed of 11–13 mph is recommended.
- *Determine the distance from the existing transmission lines:* Infrastructure for transmission of electricity from a wind farm can become expensive if new transmission lines need to be installed.
- *Availability of land:* A large amount of land is required for setting up wind farms. Determine land ownership requirements before design.
- *Understand economics:* Securing investment capital, joint ownership, and federal/state incentives can cut costs significantly.
- *Determine zoning and permitting expertise:* Obtain expertise on wind power generation and integration.
- *Determine O&M needs:* Obtain O&M needs from wind turbine manufacturers.

Additional Resources

How Wind Turbines Work:
http://www1.eere.energy.gov/windandhydro/wind_how.html. Last accessed: July 12, 2011.
http://www1.eere.energy.gov/windandhydro/. Last accessed: July 12, 2011.
http://www.powernaturally.org/. Last accessed: July 12, 2011.

Wind Energy Tools:

http://www.nrel.gov/learning/ep_wind.html. Last accessed: July 12, 2011.
http://www.nrel.gov/analysis/analysis_tools_tech_wind.html. Last accessed: July 12, 2011.
http://www.nrel.gov/docs/fy05osti/36971.pdf. Last accessed: July 12, 2011.
http://swera.unep.net/index.php?id=data_search&action_method=external_archive_query&datatype=4,70&geoarea=-1&energycategory=87&orderby=geoarea. Last accessed: July 12, 2011.

4.4.1.4 Geothermal Energy

Principle

Geothermal energy sources are classified in terms of the measured temperature as low (<100 °C), medium (100–150 °C), and high temperature (>150 °C). Geothermal energy is usually extracted with ground heat exchangers. The extracted heat is used directly for electricity production or for heat pump applications. Additional information on geothermal systems is provided in Section 2.5 of Appendix C.

Based on the type of application, geothermal energy can be utilized for direct use, for electricity production, or as heat pumps.

Direct Use

- Heat is produced directly from soil or from hot water in the earth. A well is drilled into the geothermal reservoir to provide a steady stream of hot water.
- A mechanical system is used to bring the hot water up to the surface and is directly used, e.g., to heat water for pools and aquaculture, or for space heating.

Electricity Production

- Earth's heat is used to generate electricity. Heat from the earth's magma in the form of steam is used to generate electricity via a turbine and generator.
- Dry steam, flash steam, and binary systems are three configurations for thermal energy recovery for mechanical power conversion.
- Dry steam power plants draw from underground sources of steam, which is directly used to run a turbine/generator unit.
- Flash steam power plants are the most common and use geothermal reservoirs of water with temperatures greater than 360 °F (182 °C). When water flows up, it is partially converted into steam because of decreasing pressure. The steam is then separated from the water and used to power a turbine/generator.
- Binary cycle power plants operate on water at lower temperatures of about 225–360 °F (107–182 °C). Binary cycle plants use the heat from the hot water to boil a working fluid, usually an organic compound with a low boiling point. The working fluid is vaporized in a heat exchanger and used to turn a turbine.

Heat Pump

- Heat pumps are used to heat and cool buildings. Over broad areas of the United States, near-surface soils maintain a temperature between 50 and 60 °F (10 and 16 °C). This temperature is warmer than the air above it in the winter and cooler in the

summer, and can make heat pump applications economically competitive with fossil-fuel heating systems, and especially competitive with electrical heating and ambient-cooled air conditioning.

- In the winter, the heat pump removes heat from a ground-coupled heat exchanger and "pumps" the heat into the indoor air delivery system. In the summer, the process is reversed, and the heat pump moves heat from the indoor air into the heat exchanger.
- Geothermal heat pumps consume much less energy than conventional heating systems because they draw heat from the ground.

Additional Resources

Geothermal Energy Utilization:
http://www.nrel.gov/learning/re_geothermal.html. Last accessed: July 12, 2011.
http://www.nrel.gov/analysis/tech_geo_analysis.html. Last accessed: July 12, 2011.
http://www1.eere.energy.gov/geothermal/. Last accessed: July 12, 2011.

4.4.1.5 Biogas

Principle

Biogas refers primarily to the methane and carbon dioxide generated during sludge anaerobic digestion in tanks of wastewater treatment plants. In the aerobic digestion process, microorganisms convert organic material to biogas in the absence of oxygen.

Generation of Electricity

The biogas is used to generate electricity using a fuel cell, gas engine, or gas turbine. Fuel cells are electrochemical cells that produce electricity from fuel. Additional information on fuel cells is provided in Section 2.6 of Appendix C. When the fuel reacts with an oxidizing agent, electricity is produced.

- Applications include grid-connected power generation, cogeneration of power and heat, off-grid power supply, emergency power, and distributed generation.
- Based on efficiency, type of electrolyte used, and operating temperature, different types of fuel cells exist. They are polymer electrolyte membrane (PEM), direct methanol, alkaline, phosphoric acid, molten carbonate, solid oxide, and regenerative.
- Net electrical efficiency can attain 42–47%. Low-temperature systems are less efficient than intermediate- and high-temperature systems.

Biogas is also used to generate power using a gas engine or gas turbine. Further information on the use of biogas for electricity generation is provided in Section 2.7 of Appendix C. The principal concern with the use of biogas is that it must be cleaned of siloxanes prior to use, which can be an expensive process, depending upon the quality of the product gas. Piston-actuated gas engines have a lower efficiency but a higher tolerance for contaminants, whereas gas turbines have higher efficiencies but almost no tolerance for contaminants.

- Utilization of biogas in gas engine systems is typically referred to as cogeneration because of the simultaneous generation of power.
- Overall cogeneration plant efficiencies using a gas engine can reach more than 90% and leads to energy savings of approximately 40% compared to separate power and heat generation equipment.
- The primary components of a gas engine are an engine/generator unit and heat exchangers for utilization of waste heat.
- Power plant electrical switch and control systems distribute the electricity and manage the engine. Hydraulic equipment controls the heat distribution.

Additional Resources

Fuel Cell Technology:
http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/index.html. Last accessed: July 12, 2011.

Biogas Cogeneration:
http://www.gepower.com/corporate/ecomagination_home/biogas.htm. Last accessed: July 12, 2011.

4.4.2 Leading Renewable Energy Providers

4.4.2.1 Solar Photovoltaic

Today there are many solar photovoltaic providers, some specializing in manufacturing panels or mounting systems, others operating as engineering, procurement, and construction (EPC) contractors, and yet others vertically integrated. The number of providers grows every day, with more companies entering the market as solar PV becomes more widely accepted and affordable.

Industry Associations Provide Tools to Identify Local Providers:
www.findsolar.com. Last accessed: July 21, 2011.

> The result of a partnership between the American Solar Energy Society (ASES) and Cooler Planet, it provides a business directory of solar providers plus other tools to help assess, procure, and finance solar systems.

http://seia.org/cs/membership/member_directory. Last accessed: July 21, 2011.

> The Solar Energy Industries Association is the national trade association for the solar industry. The 1,000-member directory has a search feature to locate providers by state, business type, or keyword.

In addition, most photovoltaic panel manufacturers have networks of project developers and authorized installers. Some prominent names include the following:

Suntech:
http://am.suntech-power.com. Last accessed: July 21, 2011.

> The largest silicone PV manufacturer in the world, yet they only provide panels through their partner network.

First Solar:
http://www.firstsolar.com. Last accessed: July 21, 2011.

> Constantly ranked among the largest world manufacturers of PV modules.

Sharp:
http://www.sharpusa.com/SolarElectricity.aspx. Last accessed: July 21, 2011.

> With probably the oldest PV manufacturer, Sharp also perform sales through their independent certified installers.

Among the installers and vertically integrated solar providers, some key players are the following:

SunPower Corp.:
http://us.sunpowercorp.com/. Last accessed: July 21, 2011.

> A vertically integrated firm providing solar panels.

SunEdison:
http://www.sunedison.com/. Last accessed: July 21, 2011.

> Now a subsidiary of MEMC, SunEdison is an international developer of solar projects focused on the commercial and utility markets.

Solar City:
www.solarcity.com. Last accessed: July 21, 2011.

Full service provider of residential and commercial systems, servicing Arizona, California, Colorado, Hawaii, Maryland, Massachusetts, New Jersey, New York, Oregon, Pennsylvania, Texas, and Washington, DC.

REC Solar:
http://www.recsolar.com/. Last accessed: July 21, 2011.

One of the largest in the nation by watts installed, REC Solar services Arizona, California, Colorado, Hawaii, New Jersey, and Oregon offering turn-key solutions from residential to utility systems.

4.4.2.2 Concentrating Solar Power

Solarlite:
www.solarlite.de. Last accessed: July 21, 2011.

Manufacturer and supplier of solar thermal parabolic trough plants. At small scales they can generate process heat instead of electricity.

Abengoa Solar:
www.abengoasolar.com/corp/web/en/index.html. Last accessed: July 21, 2011.

Provides solar thermal technologies to meet industrial heat and steam requirements.

Sopogy:
http://sopogy.com/. Last accessed: July 21, 2011.

Provides micro CSP systems for distributed power generation, process heat and solar air conditioning.

Amonix:
http://amonix.com/. Last accessed: July 21, 2011.

Designer and manufacturer of concentrated photovoltaic (CPV) commercial solar power systems.

SolFocus:
www.solfocus.com/en/. Last accessed: July 21, 2011.

Supplier of concentrator photovoltaic (CPV) systems.

4.4.2.3 Wind Turbines

Wind systems vary greatly in size, and choosing the appropriate turbine is highly dependent on site characteristics, wind resources, and power needs. Small systems with rated output from a few kW up to 50 kW come in varied shapes and sizes and are used in residential and localized industrial applications (e.g., water pumping or telecommunications). Then there are medium turbines in the range 50–250 kW that can serve larger commercial facilities, buildings, and large farms, as well as off-grid systems. Larger turbines (900 kW to 2 MW) are mainly used in utility-scale arrays and seldom used as a standalone solution.

Small:

Windspire Energy Inc.
http://windspireenergy.com. Last accessed: July 21, 2011.

> Offers a vertical axis wind system rated at 1.2 kW that eliminates the need for large towers and is suitable for urban environments.

Southwestern Windpower:
http://www.windenergy.com/. Last accessed: July 21, 2011.

> Leader in small turbines (3 kW and under).

Bergey Windpower:
www.bergey.com/. Last accessed: July 21, 2011.

> A long-established manufacturer with two well-known products rated at 1 and 10 kW.

Gaia-Wind:
www.gaia-wind.com. Last accessed: July 21, 2011.

> Offers a two-bladed 11 kW turbine. Based in the United Kingdom.

Endurance Wind Power:
www.endurancewindpower.com. Last accessed: July 21, 2011.

> Manufacturer offering several models from 5 to 50 kW.

Enertech:
http://www.enertechwind.com/index.html. Last accessed: July 21, 2011.

> Manufacturer of a 40 kW turbine widely used in the United States.

Medium:

Northern Power Systems:
http://www.northernpower.com/. Last accessed: July 21, 2011.

> Offers a 100 kW and a new 2.3 MW direct drive turbine.

Polaris America:
www.polarisamerica.com/. Last accessed: July 21, 2011.

> Has an ample turbine portfolio with a Small product line going from 10 to 50 kW and a Large line sized at 100, 500, and 1,000 kW.

Large:

Siemens: Supplier of high quality wind turbine blades and wind turbines to all parts of the world.
http://www.energy.siemens.com/mx/en/power-generation/renewables/wind-power/wind-turbines/, Last accessed: July 21, 2011.

GE Wind Energy:
http://www.ge-energy.com/wind. Last accessed: July 21, 2011.

> A branch of General Electric's Energy business, ranks near the top of the wind turbine suppliers by market share. GE's product portfolio goes from 1.5 to 4 MW for both on- and offshore applications.

Vestas:
www.vestas.com/en/. Last accessed: July 21, 2011.

> The largest supplier of utility-scale turbines, with a broad portfolio that expands from 850 kW up to a 7-MW turbine for offshore applications.

4.4.2.4 Geothermal

The use of geothermal energy to generate electricity is limited to sites with very specific characteristics (superheated aquifers reachable by current drilling technology), and so far, feasible installations have only happened on the large scale. In the United States, the average geothermal plant capacity is close to 50 MW.

The major developers of geothermal systems in the United States are the following:

Ram Power Corp.:
www.ram-power.com. Last accessed: July 21, 2011.

> Provider of geothermal energy project development and infrastructure.

Calpine Corp.:
www.calpine.com. Last accessed: July 21, 2011.

> Provider of geothermal energy project development and infrastructure.

Geothermal energy can also be harnessed to aid heating and cooling processes by the use of geoexchangers, which are much more versatile in both size and the underground conditions required to make them viable. There are many providers of geoexchange technology, and most come together at the Geothermal Exchange Organization (GEO).

In addition, the following web link has a useful search feature designed to aid in locating member companies based on expertise, services provided, and geographic location:

http://www.geoexchange.org/index.php?option=com_content&view=article&id=273&Itemid=5. Last accessed: July 21, 2011.

4.4.2.5 Bioenergy

GE:
http://www.gepower.com/prod_serv/products/recip_engines/en/index.htm. Last accessed: July 12, 2011.

Supplier of biogas cogeneration engines.

Cenergy:
http://www.2g-cenergy.com/index.html. Last accessed: July 12, 2011.

Provider of biogas cogeneration engines.

Ballard Power Systems:
www.ballard.com. Last accessed: July 12, 2011.

Supplier of fuel cell technology.

Hygrogenics:
www.hygrogenics.com. Last accessed: July 12, 2011.

Supplier of fuel cell technology.

Lynntech:
www.lynntech.com. Last accessed: July 12, 2011.

Supplier of fuel cell technology.

UTC Power:
www.utcpower.com. Last accessed: July 12, 2011.

Supplier of fuel cell technology.

4.5 Integration

Growing concerns over climate change and adoption of state-level renewable portfolio standards and incentives, with accelerated cost reduction, will make renewable energy technologies a larger part of energy portfolios during the coming decades. It should also be

noted that climate change could result in unexpected changes in renewable energy resource availability. For example, changes in wind patterns need to be considered in addressing integration of renewable energy resources.

Utility-scale renewable energy systems are typically connected to existing electricity grids. As the market share of renewable energy grows, stability and operation of the electricity grid will be increasingly critical. Some aspects that need to be considered during grid integration of renewable energy technologies are provided in this section with an overview of integration challenges, methods, and considerations for grid integration. Further information on integration can be found in the additional resources section at the end of this section.

4.5.1 Integration Challenges

- Electricity supply and demand must be met to operate an efficient power station. Integration challenges are predominant for solar PV and wind technologies because of their variability in generating electricity.
- Variability of electricity production from solar and wind technologies leads to increased complexity of operating the electricity grid.
- Several states and utilities in the United States have grid interconnection standards. Some of these standards inhibit the connection of renewable energy technologies (mostly solar PV systems) to the electricity grid.

4.5.2 Integration Methods

4.5.2.1 Solar PV Systems

- Solar PV systems are integrated with the electricity grid through inverters and transformers. The inverters are used to convert DC to AC and the transformers are used to convert low voltage to high voltage before feeding into the main electricity grid.
- When solar PV systems are implemented, use of several inverters in parallel should be considered, so that failure of an inverter does not prevent electricity from being transmitted to the main grid.

4.5.2.2 Wind Turbine

- Electricity produced from wind turbines is collected in a medium-voltage (25–35 kV) power collection system. Wind turbines are typically located 1 to 10 miles from high-voltage transmission lines in order to minimize costs associated with interconnection.
- Transformers located adjacent to the wind tower are used to convert the low-voltage power from the turbine to the higher voltage of the electricity collection system.
- Substations are typically used for passing electricity from wind turbines to the utility grid. Plant isolation breakers and power quality monitors are present in the substation to protect the grid and wind turbines. A system of switches and overhead infrastructure is used to connect the substation to the utility's power lines.

4.5.3 Considerations for Grid Integration

- Distributed photovoltaic systems design and technology requirements can be used to develop a set of conceptual system designs to integrate solar PV systems to the electricity grid.
- Solar energy grid integration systems (SEGIS) can be used to incorporate advanced functionality and integration with the electricity grid.
- Utility models and analysis and simulation tools can be used to review current utility studies, models, and software applications that are used in grid planning.
- Cyber security analysis can be used to examine the potential security implications of high penetration of renewable electricity supply, which will require high levels of information technology and control systems.
- Consider power systems planning and emerging practices suitable for evaluation of the impact of high-penetration solar PV and wind energy systems.
- Utilize prototype field tests to evaluate key characteristics of a new renewable energy technology system that maximizes grid value.
- Differences between intermittent PV and solar power systems, as compared to base load geothermal power systems, play a role in evaluating integration issues.

Additional Resources

Solar Photovoltaic System Integration:
http://www1.eere.energy.gov/solar/segis.html. Last accessed: July 12, 2011.
http://www.nrel.gov/docs/fy09osti/45061.pdf. Last accessed: July 12, 2011.
http://www.nrel.gov/docs/fy08osti/42675.pdf. Last accessed: July 12, 2011.
http://www.nrel.gov/docs/fy08osti/42292.pdf. Last accessed: July 12, 2011.

Wind System Integration:
http://www.nrel.gov/wind/systemsintegration/data_resources.html. Last accessed: July 12, 2011.
http://www.nrel.gov/wind/systemsintegration/capabilities.html. Last accessed: July 12, 2011.
http://www.nrel.gov/wind/systemsintegration/faqs.html. Last accessed: July 12, 2011.
http://www.nrel.gov/wind/systemsintegration/projects.html. Last accessed: July 12, 2011.
http://www.nyserda.org/publications/wind_integration_report.pdf. Last accessed: July 12, 2011.

4.6 Handling Variability

Handling variability of renewable energy resources is a key criterion for implementation. When variability is of concern, two types of methods are employed: (1) use of hybrid designs, and (2) utilization of storage technologies.

4.6.1 Hybrid Designs

- The application of a hybrid design allows the use of multiple renewable technologies depending on the location and resources available.

- Hybrid designs consist of a combination of solar and wind technologies to allow the capture of maximum sun in the summer and maximum wind in the winter.

4.6.2 Storage

One hurdle to widespread adoption of renewable power is reliability. Sources of renewable energy, such as the sun and wind, are not consistently available. Energy generation capacity in excess of instantaneous demand may not be utilized, whereas excess demand results in an unacceptable lack of energy availability. Renewable energy storage provides a means of load balancing. Although all renewable energy storage systems result in a net loss of energy, their use allows energy to be transferred from low peak to high peak, which increases its value, and allows energy to be available on demand (firm power), thereby avoiding grid instability. These advantages of renewable energy storage increase the reliability of renewable power, making it a more viable replacement for conventional sources of power.

- There are currently seven main types of renewable energy storage available at a utility scale: batteries, pumped-storage hydroelectricity, compressed air storage, flywheels, supercapacitors, hydrogen fuel cells, and seasonal thermal storage.
- Of all the energy storage technologies, pumped hydro storage is the most established and is currently cost effective for its purpose. In fact, pumped storage hydroelectricity accounts for 3% of the world's electricity. In addition, it can achieve one of the highest cycles per lifetime at one of the lowest costs. Pumped hydro, however, is constrained by geologic features. Other technologies that rely on specific geologic formations include compressed air energy storage and some forms of thermal storage.
- Costs of batteries, while similar, can be highly dependent on the cost of input materials, which fluctuates in the market. Batteries can be implemented at all locations. There are more than half a dozen types of batteries that show varying degrees of promise, including polysulfide bromide flow batteries, vanadium redox flow batteries, zinc bromine flow batteries, sodium sulfur batteries, lithium ion batteries, traditional lead–acid batteries, and metal–air batteries.
- Polysulfide bromide flow batteries (PSBs), vanadium redox flow batteries (VRBs), and zinc bromine flow batteries (ZBRs) are collectively known as flow batteries. These typically share similar features such as cycles/lifetime, discharge time, and energy density.
- VRBs have an efficiency of 85%, which is higher than the 75% of PSBs and ZBRs. Although NaS batteries have a high energy density, they are currently very expensive to operate because they must be kept at 300 °C. Lithium ion batteries also have a high energy density; they are slightly more efficient than NaS batteries and can achieve more cycles per lifetime.
- Lead–acid batteries are one of the few proven battery technologies. However, their price is highly sensitive to the price of lead, and at the conclusion of their useful life they require extensive recycling. Of the batteries, VRB, lead–acid, and NaS batteries are being utilized at a commercial level.
- Other technologies, such as flywheels and supercapacitors, are not ideal for storage for longer than a few seconds or minutes. These technologies, however, provide superior electricity quality and can come online almost instantaneously, providing bridging power between two longer-term sources of electricity.

Additional Resources

Integration and storage:
http://www.oe.energy.gov/renewable.htm. Last accessed: July 12, 2011.

> This web link provides information on renewable and distributed systems integration (RDSI) and focuses on integrating renewable energy, distributed generation, energy storage, thermally activated technologies, and demand response into the electric distribution and transmission system.

Energy storage systems program:
http://www.sandia.gov/ess/. Last accessed: July 12, 2011.

> This web link provides information on the energy storage systems (ESS) program. The goal of ESS is to develop advanced energy storage technologies and systems, in collaboration with industry, academia, and government institutions, that will increase the reliability, performance, and competitiveness of electric generation and transmission in utility-tied and off-grid systems.

Handing wind power variability:
http://www.nrel.gov/docs/fy06osti/39955.pdf. Last accessed: July 12, 2011.

> This web link provides information on grid impacts of wind energy variability and recent assessments from a variety of utilities in the United States.

4.7 Permitting

4.7.1 Approach

Project permitting is a critical function for the success of any energy generation project. Every state has a unique approach to permitting, but there are some general guidelines that can be followed in getting off on the right foot. The California Association of Resource Conservation Districts guide has identified 11 key activities required to successfully navigate the permitting process that can lead to a successful desalination project with renewable energy generation sources on or adjacent to the site.

- *Careful project design:* Design your project with regulation in mind to minimize rework and costly delays.
- *A thorough project description for regulators:* The more effectively you describe your work, the less likely you will be to get show-stopper questions or delays due to lack of project understanding.
- *Contact agencies early:* Permitting can easily become a long-drawn-out process, so get started as soon as possible. Learn the rules that regulators have set up and get to know your regulators well.
- *Involve the public and media:* Controlling your message is important, and you do not want the press or others dictating your project's motives and image. Involve the

public early, be forthright, and work to communicate your message well to the press to enlist them as an ally.

- *Positive, nonadversarial position:* The permitting process can be challenging with many conflicting views on the project. Diplomacy and courtesy will get you much further than animosity.
- *Pay attention to details:* Follow the rules, be prompt with responses and meeting with regulators, and do not cut corners. Somebody always pays in the end.
- *Be willing to negotiate:* A variety of public interests may be imposed on your project that you may not have conceived of earlier. Staying sensitive to regulator and public needs, within reason, will help keep your project moving forward.
- *Ask questions of regulators if there is any uncertainty:* The more accurate and complete your formal submittals are to your permit agencies, the less likely regulators are to pick your submissions apart. Frequent questioning also sends the message that you really want to comply with the rules that the regulator is administering.
- *Get everything in writing:* Misunderstandings can be minimized by taking extra time to carefully manage all correspondence and get it properly documented. You also develop a documented record of responsiveness and compliance, which can smooth the resolution of follow-on questions, support continuity through personnel changes, and so forth.
- *Minimize project impacts:* Though every project has budget constraints, understanding the regulations and actively working to minimize negative impacts on and off site will go a long way in navigating the permitting process.
- *Frequent, proactive follow-up:* Follow-up with permitting agencies will result in ensuring that all new permitting requirements are met before the construction of the plant.

4.7.2 Typical Permits Required for Desalination

Every state has a unique approach to permitting. By applying the approach just discussed to a particular region, an organization can be well served. A list of permits that would typically be required in the California market follows. Any on-site power generation through renewable energy supplies or future offshore, directly connected systems would need to comply with and be incorporated into these permits. The federal permits identified here will be pertinent throughout the United States and should be considered carefully. Because federal regulations generally serve as templates for state regulations, this California permit profile will also exemplify many regulatory steps for most other states.

- California Regional Water Quality Board
    - National Pollution Discharge Elimination System (NPDES)
    - Federal Clean Water Act Section 401 permit for discharges onto waters of the United States
- California Air Resources Board: Greenhouse gas emissions
- California Environmental Quality Act: Environmental impact report
- California Fish and Game: CEQA review and potential 404 permitting

- California Coastal Commission: Coastal development permit: permits for projects installing infrastructure in coastal areas
- US Army Corps of Engineers: Wetlands permits or Section 10 permits for projects "working to erect structures in or affecting navigable waters," which include all waters affected by tidal influence or otherwise navigable
- US Fish and Wildlife Service: Endangered Species Act compliance (Sections 7 and 10)
- National Environmental Pollution Act: NEPA environmental report
- California Rivers and Harbors Act: Permit

Additional Resources

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Appendix A

Utility Case Studies

The objective of the utility case studies was to obtain information on energy utilization, energy minimization strategies, and renewable energy utilization. Nine different facilities utilizing conventional and renewable resources were surveyed during the study. A comparison of reuse and desalination plants surveyed is shown in Table A.1. Utilities surveyed were located in the United States, Singapore, and Australia. The size of the seawater desalination plants ranged from 3,470 to 13,880 m^3/h (22 to 88 MGD), the size of brackish water desalination plants ranged from 552 to 1,261 m^3/h (3.5 to 8 MGD), and the size of water reuse plants ranged from 1,734 to 4,731 m^3/h (11 to 30 MGD).

Treated water from all brackish water and seawater desalination plants is used for potable purposes. Treated water from reuse plants is used for groundwater replenishment, indirect potable reuse (irrigation), or industrial (boiler feed) applications. An example of feed and treated water quality obtained from a water reuse and seawater desalination plant is provided in Table A.2. Typical process flow schematics of treatment plants utilized for reuse and seawater desalination are shown in Chapter 3 (Figures 3.2 and 3.3). A summary of energy minimization strategies employed and renewable energy implementation lessons learned follows.

Table A.1. Comparison of Energy Consumption Rates for Utilities Surveyed

Utility	Type of Plant	Capacity m^3/h (MGD)	End Use	Feed TDS	Permeate TDS	Specific Energy Consumption, kWh/ m^3
1	Reuse	4,731 (30)	GWR, IPR	850 mg/L	30 mg/L	—
2	Reuse	1,734 (11)	Industrial, IPR	552 mg/L	26 mg/L	0.98
3	Reuse	3,469 (22)	IPR	712 mg/L	< 150 mg/L	—
4	Seawater desalination	5,993 (38)	DW	37,000 - 40,000 mg/L	< 200 mg/L	3.6
5	Seawater desalination	10,410 (66)	DW	36,700 mg/L	275 mg/L	3.3
6	Seawater desalination	13,880 (88)	DW	40,500 mg/L	< 80 mg/L	3.5
7	Seawater desalination	3,943 (25)	DW	< 28,500 mg/L	< 360 mg/L	3.9
8	Brackish water desalination	552 (3.5)	DW	2,300 mg/L	< 320 mg/l	0.94
9	Brackish water desalination	1,261 (8)	DW	2,000 mg/L	< 150 mg/L	1

Table A.2. Feed and Treated Water Quality for Reuse and Seawater Desalination Treatment Plants

Parameters	Feed Water to Advanced Water Treatment Plant	Treated Water—Reuse	Raw Seawater	Treated Water—Seawater Desalination
pH	7	5.7	7.7	6.9
Alkalinity, mg/L as CaCO3	340	18	94	3
Conductivity, µS/cm	1,600	50	53,600	413
Total dissolved solids, mg/L	850	30	35,600	275
Sodium, mg/L	185	8.2	10,700	98
Potassium, mg/L	18	NA	490	5
Calcium, mg/L	50	0.051	424	2
Magnesium, mg/L	26	0.017	1,370	5
Iron, mg/L	0.3	< 0.1	0.005	<0.05
Silica, mg/L	20	0.47	0.12	<0.05
Sulfate, mg/L	140	< 2	2,740	11.8
Chloride, mg/L	200	5	19,700	164
Phosphate (mg/L as PO4)	10	NA	<0.015	<0.003
Nitrate (mg/L as NO3)	NA	0.19	0.172	<0.009
Boron (mg/L)	NA	NA	4.7	0.88

NA: Data not available.

A.1 Energy Consumption

The distribution of energy consumption during wastewater treatment is shown in Figure A.1. Energy consumption was calculated through SCADA systems and energy audits. A process flow schematic of a treatment plant is shown in Figure A.2.

A summary of energy consumption information provided is as follows:

A.1.1 Water Reuse Plants

- The reuse plants surveyed consisted of advanced treatment processes including MF, RO, and UV. The total energy consumption was on the order of 1 kWh/m^3.
- The greatest energy consumption was due to the operation of pumps (more than 50% of total energy consumption). After pumps, blowers (16% of total energy consumption) and aerators (8% of total energy consumption) also consume large amounts of energy.

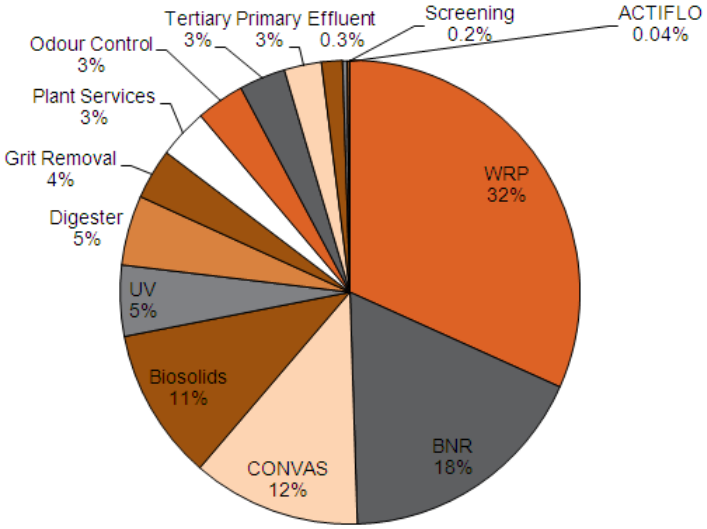

Figure A.1. Energy use by process during wastewater reuse. CONVAS is conventional activated sludge; BNR is biological nitrogen removal; WRP is water recycling plant.

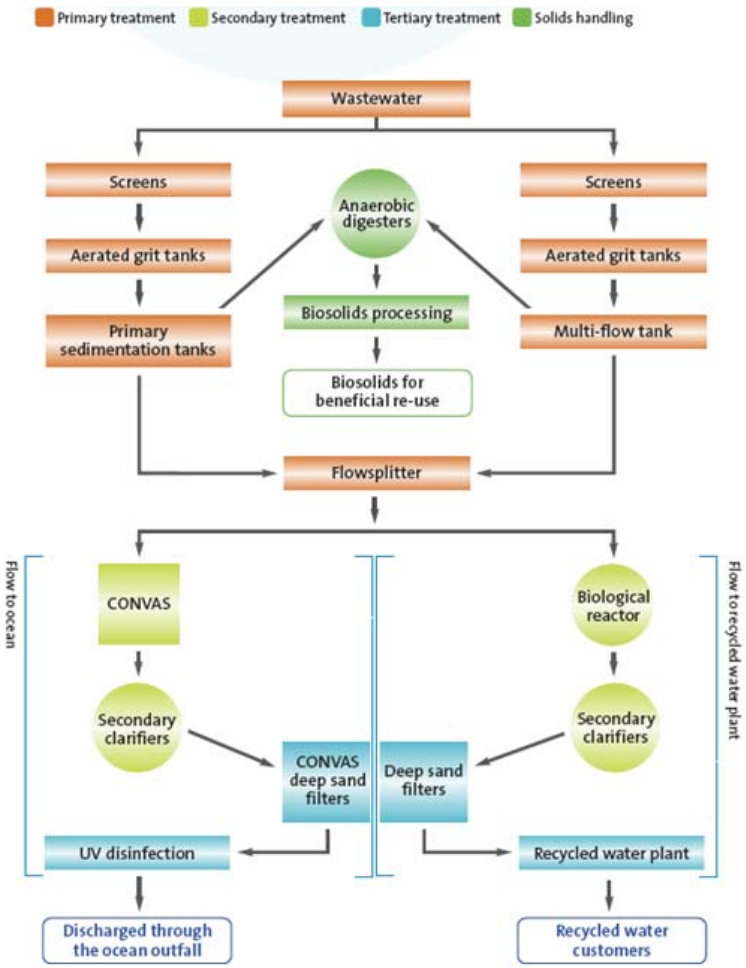

Figure A.2. Process flow schematic of wastewater treatment and recycled water plant, for which energy consumption is provided in Figure A.3.

A.1.2 Seawater Desalination Plants

Typical energy consumption in a seawater RO desalination plant is shown in Table A.3. Energy consumption with flow rate for a seawater RO desalination plant is shown in Figure A.3.

- The total energy consumption was on the order of 3–4 kWh/m^3. The energy consumption fluctuated significantly when the capacity of the plant varied. Energy consumption was lowest when the plant was operated at maximum capacity.
- The greatest energy consumption was due to the operation of high-pressure energy pumps for desalination (more than 75% of total energy consumption).

Table A.3. Typical Energy Consumption of Various Components during Seawater Desalination

Component	Specific Energy Consumption, kWh/m^3
Raw water pumping	0.39
Pretreatment and desalination	2.865
Post-treatment	0.012
High-service pumping station	0.3
General (buildings, heating, cooling)	0.04
Total energy consumption	3.607

A.2 Reported Energy Minimization Strategies

The following is a list of strategies reported by the utilities surveyed:

- Monitoring of energy efficiency of pumps (pump efficiency curves) to determine if the pumps and motors are operating close to the best efficiency point.
- Replacing older pumps and motors with newer premium efficiency models.
- Installation of VFDs to control motor speed and reduce energy consumption.
- Utilization of smaller RO trains and larger high pressure pumps led to minimization of energy consumption for seawater desalination.
- ERDs (Pelton wheels, pressure exchangers) for seawater desalination were installed in the first pass and were more than 90% efficient in recovering the pressure from brine.
- ERDs (turbochargers) for brackish water desalination were installed between the first and second stage to operate as booster pumps. No significant energy minimization was obtained by using ERDs for brackish water treatment.

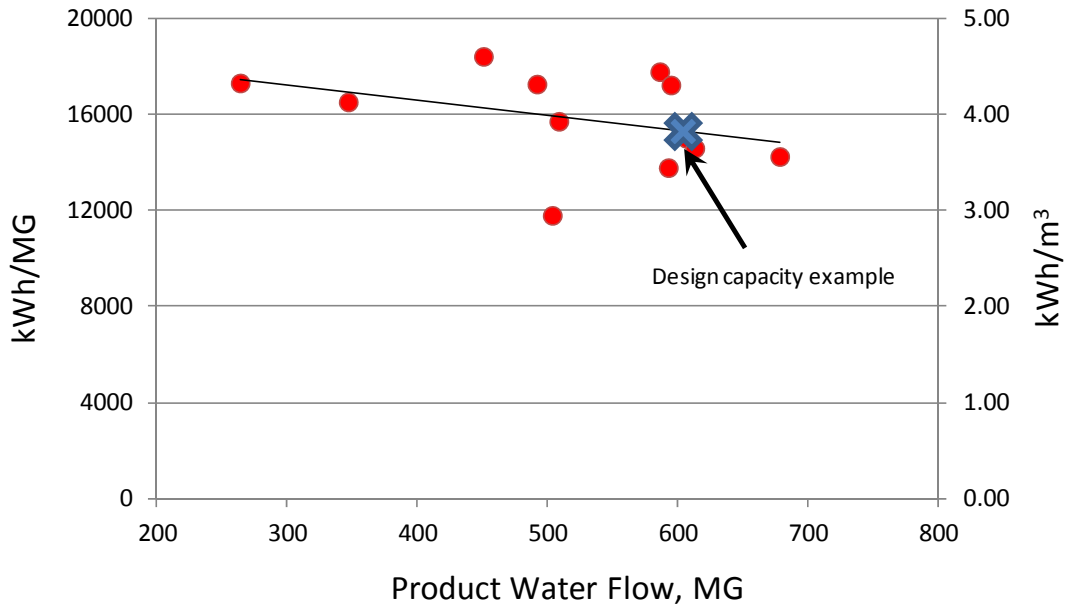

Figure A.3. Overall energy consumption for seawater desalination as a function of product water flow for one utility. The mark "X" denotes an example of design capacity. Energy consumption is higher when the plant is operating below design capacity.

A.3 Renewable Energy Utilization

A comparison of renewable energy utilization opportunities and drivers for the utilities surveyed is shown in Table A.4. Challenges encountered by the utilities for renewable energy utilization is shown in Table A.5.

- Solar PV and biogas cogeneration were the two types of renewable energy utilization (on site) for water reuse plants. Renewable energy provided 20% of the total energy consumption for the plants.
- Wind farms (off site) were utilized for the seawater desalination plants surveyed. Renewable energy provided 100% of the total energy consumption for the plants.
- All types of renewable energy utilized were connected to the utility grid and power was supplied to the plant through the utility grid (in addition to any on-site generation).
- Key drivers for renewable energy utilization were the funding available and social responsibility (reduced GHG emissions).
- All the utilities received funding from government and utility power providers in the form of direct funding, power purchase agreements, incentives, and rebates.
- Key challenges for implementation of renewable energy were ROI, footprint requirements, and integration of renewable energy with utility grid. There were no hurdles due to permitting requirements.

- ROI was a key challenge for the utilities that implemented renewable energy. Footprint requirements were high for installing solar PV panels. Solar PV panels were installed on concrete tanks where appropriate.
- Integration of renewable energy power to utility electricity grid was a challenge. When solar PV panels were utilized, several inverters were connected in parallel to ensure a constant supply of power to the electricity grid and maintain load.

Table A.4. Comparison of Renewable Energy Utilization Opportunities and Drivers for Utilities Surveyed

Utility	Type of Plant	Renewable Energy	% Use of Renewable	Onsite/Offsite	Funding/Incentives	Drivers
1	Reuse	Solar PV	20%	On site—grid-connected	Energy utility	Subsidized, sustainability, social resp.
2	Reuse	Biogas cogeneration	20%	On site—grid-connected	Government funds	Subsidized, sustainability, social resp.
3	Reuse	None	0%	None	Not determined	—
4	Seawater desalination	Wind	100%	Off site—grid-connected	Government funds	Subsidized, sustainability, social resp.
5	Seawater desalination	Wind	100%	Off site—grid-connected	Government funds	Subsidized, Sustainability, social resp
6	Seawater desalination	None	0%	—	—	—
7	Seawater desalination	None	0%	—	—	—
8	Brackish water desalination	Future consideration	0%	Considering on-site solar PV/CSP	Not determined	Subsidized, sustainability, social resp.
9	Brackish water desalination	Future consideration	0%	Considering o-nsite solar PV	Not determined	Subsidized, sustainability, social resp.

Table A.5. Comparison of Renewable Energy Implementation Challenges for Utilities Surveyed

Utility	Plant Type	ROI	Funding	Footprint	Integration	Permitting
1	Reuse	Minus	Plus	Minus	Minus	Plus
2	Reuse	Minus	Plus	Plus	Minus	Plus
3	Reuse	ND	ND	ND	ND	ND
4	Seawater desalination	Minus	Plus	Plus	Plus	Plus
5	Seawater desalination	Minus	Plus	Plus	Plus	Plus
6	Seawater desalination	ND	ND	ND	ND	ND
7	Seawater desalination	ND	ND	ND	ND	ND
8	Brackish water desalination	Minus	ND	ND	ND	ND
9	Brackish water desalination	Minus	Minus	Plus	ND	ND

Notes: Plus: Denotes that the parameter was favorable for renewable energy implementation. Minus: Denotes that the parameter was unfavorable for renewable energy implementation. ND: Not decided on implementation of renewable energy.

Appendix B

Energy Consumption and Minimization Strategies

B.1 History of Desalination

Desalination in the form of distillation was first utilized aboard ships to avoid the possibility of depleting onboard fresh water supplies (Seigal and Zelonis, 1995). During the 17th century, Japanese sailors used a distillation technique where water was boiled in pots and bamboo tubes were used to collect the evaporated water (Desalination in History, 2005). Advanced distillation technology started developing in the late 18th century (Greenlee et al., 2009). Some of the first attempts at commercial desalination plants included those installed in Tigne, Malta in 1881 and in Jeddah, Saudi Arabia in 1907 (Desalination in History, 2005). The first countries to use desalination on a large scale for municipal drinking water production were in the Middle East. Seawater distillation plants were first developed in the 1950s, and in the 1960s, the first industrial desalination plant was opened in Kuwait (Greenlee et al., 2009). In the late 1960s, membranes began to enter the desalination market, and the first successful RO plants used brackish water as feed (Reverse Osmosis, 1993).

Over the past 40 years, dramatic improvements in RO membrane technology have elevated RO to be the primary choice for new desalination facilities. Since the 1960s and 1970s, developments in both distillation and membrane technology have led to exponential growth in world desalination capacity (Greenlee et al., 2009). Today, over 15,000 desalination plants are in operation worldwide. The Middle East holds approximately 50% of the world's production capacity. In 2005, Israel opened the world's largest RO seawater desalination facility, with a production capacity of more than 85 MGD (Sauvet-Goichon, 2007). The distribution of desalination production capacity by process technology is shown in Figure B.1 (a) and Figure B.1 (b) for the world and the United States, respectively. For the world, membrane and thermal technologies have an equal share of production capacity. But, in the United States, a major proportion of desalination production capacity is due to the application of RO (about 69%). The use of thermal technologies such as MED and MSF is less than 2% combined.

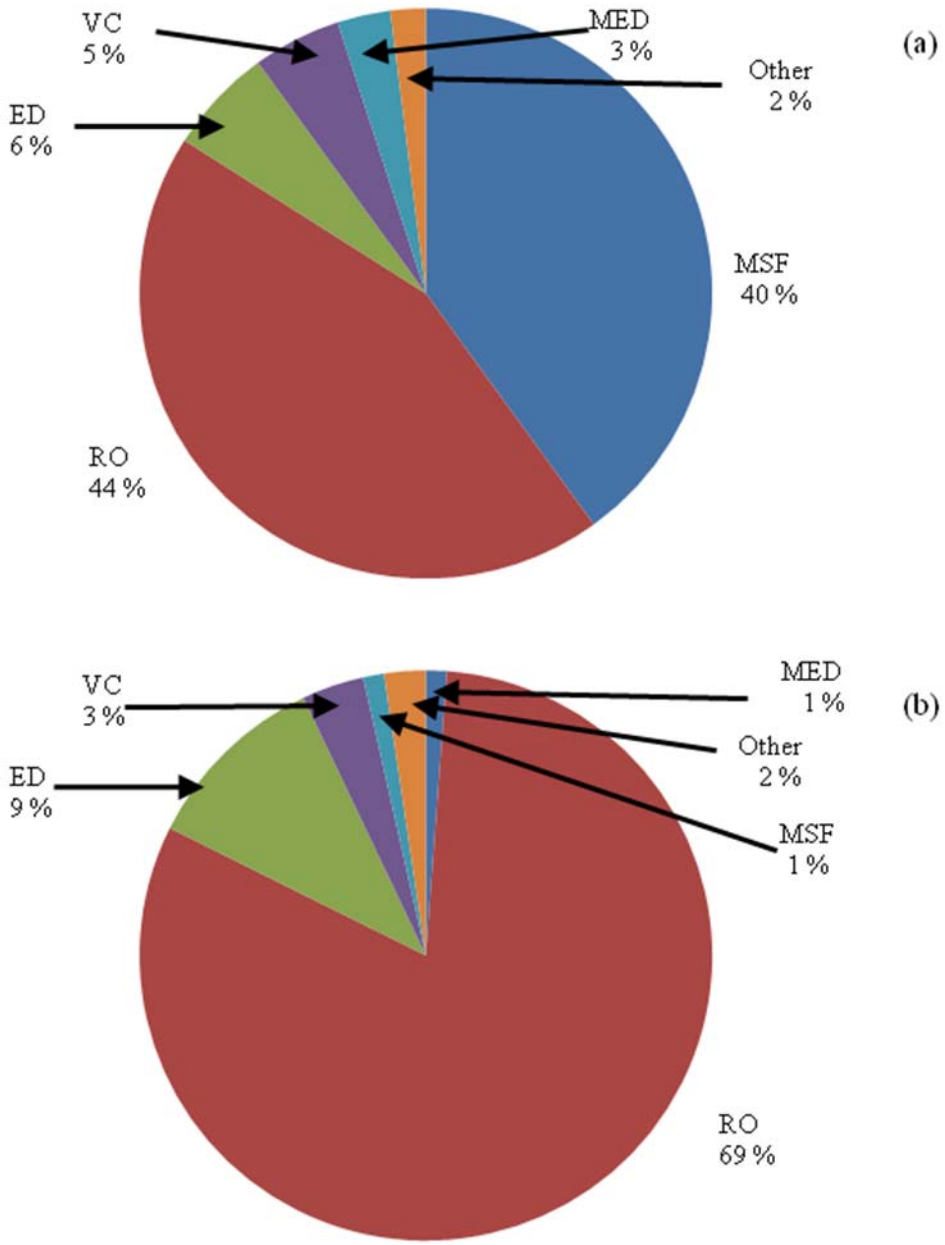

Figure B.1. Distribution of desalination production capacity by process technology for (a) the world and (b) the United States. Adapted from Greenlee et al., 2009; Murakami, 1995; Zhou and Tol, 2005). *Note:* MED: multieffect distillation; MSF: multistage flash; RO: reverse osmosis; ED: Electrodialysis; VC: vapor compression.

B.2 Desalination Technology Background

Desalination technologies can be broadly categorized into two major categories: thermal and membrane. A classification of the major desalination processes is shown in Figure B.2. A brief description of the various processes involved is provided in the following subsections.

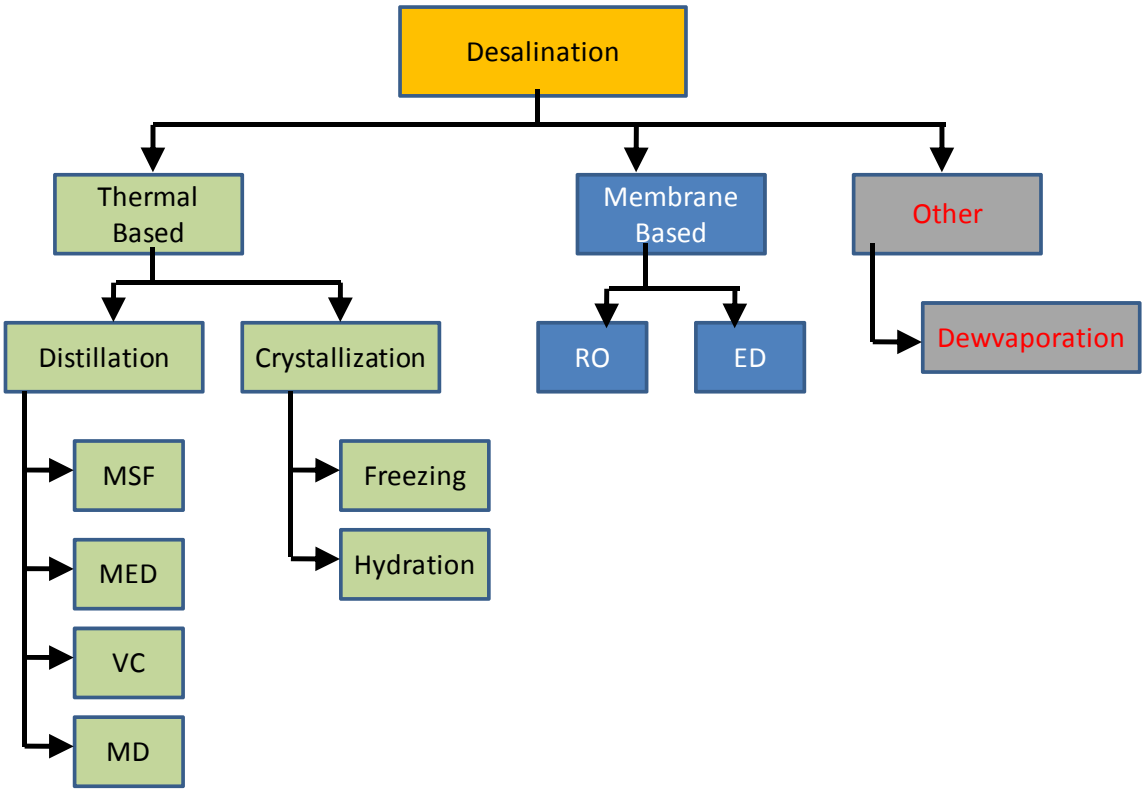

Figure B.2. Classification of major desalination processes.

B.2.1 Thermal-Based Desalination

The principle of thermal-based desalination processes depends on phase transition by energy addition or removal to separate fresh water from saline water. The most important thermal distillation processes are multistage flash (MSF) and multieffect distillation (MED). Other thermal distillation processes are vapor compression (VC) and membrane distillation (MD). Freezing and hydration are crystallization processes based on heat. Thermal-based distillation processes are described in brief in the following subsections.

B.2.1.1 Multistage Flash

The MSF process has been the predominant process for the desalination industry, which has a market share close to 60% of the total world production capacity (He and Yan, 2009). A schematic of the MSF process is provided in Veolia Water's Web site (Veolia Multistage Flash, 2011). This process is based on the generation of vapor from seawater or brine through sudden pressure reduction when seawater enters an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure. This process requires an external steam supply, normally at a temperature greater than 100 °C. The maximum temperature is limited by the salt concentration to avoid scaling. A low-temperature heat source can be utilized, and construction of equipment is simple in the MSF process. Due to the use of a small number of connection tubes, leakage problems and maintenance work are less than for other thermal-based processes. Also, evaporation and condensation are performed in many stages, thereby increasing efficiency.

The specific energy consumption for the MSF process is between 2.6 and 3.94 kWh/m^3 (10 and 15 kWh per 1000 gal) of water (Loupasis, 2001; Veerapaneni et al., 2007).

B.2.1.2 Multieffect Distillation

In the MED process, vapors are generated by the absorption of thermal energy by seawater (Gemma et al., 2006). A schematic of the MED process is provided at Veolia Water's Web site (Veolia Multi-effect Distillation, 2011). The steam generated at one stage or by one effect can heat the salt solution at the next stage, as the next stage is at a lower temperature or pressure. Similarly to the MSF process, the performance of the MED process depends on the number of stages or effects. MED plants normally use an external steam supply at a temperature greater than 100 °C. In a typical large plant, the presence of 8–16 effects is possible. The conventional MED process is the oldest method used to desalinate seawater in large quantities. Model MED units use horizontal or vertical falling evaporators in seawater desalination (Darwish et al., 2006). The low-temperature horizontal MED process is thermodynamically the most efficient of all thermal processes currently in use (Ophir and Lokiec, 2005). Major features of the MED process include the simultaneous transfer of latent heat on both sides of the heat transfer surface, utilization of aluminum tubes that permit a large heat transfer area, and short start-up periods with little time loss for heating up. The specific energy consumption for the MED process is between 1.84 and 2.63 kWh/m^3 (7 and 10 kWh per 1000 gal) of water (Loupasis, 2001; Veerapaneni et al., 2007).

B.2.1.3 Vapor Compression

VC desalination can be either thermal vapor compression (TVC) or mechanical vapor compression (MVC). The operation principle for the generation of distilled water from salt water is the same as for the MED process. Additionally, in the TVC and MVC processes, after initial vapor is generated from the saline solution, the vapor is thermally or mechanically compressed to achieve additional production. A schematic of the VC process is provided at Veolia Water's Web site (Veolia Vapor Compression, 2011). The VC process takes advantage of the principle of reducing the boiling point temperature by reducing the pressure. Methods used to condense water vapor to produce sufficient heat to evaporate incoming seawater are a mechanical compressor and a steam jet. Units have been built in a variety of configurations to promote the exchange of heat to promote evaporation (Kalogirou, 2005). The low-temperature VC process is a simple, reliable, and efficient process requiring only power. The use of a high-capacity compressor allows operation at temperatures below 70 °C, which reduces the potential for scale formation and corrosion. In general, the VC process is used for small-scale desalination plants. The power consumption for large units is approximately 7.89 kWh/m^3 (30 kWh per 1000 gal) of product water (Khawaji et al., 2008).

The performance of MSF and MED processes is directly proportional to the number of stages or chambers. These processes require more energy than membrane technologies but can produce water with much lower total dissolved solids (TDS) concentrations than membranes: less than 25 mg/L for thermal systems compared to 500 mg/L from many membrane systems (USBR, 2003). Although the energy requirement is independent of the feed water salinity, scaling caused by the accumulation of mineral deposits on heat exchange surfaces can disrupt the performance of MED systems by restricting water flow and reducing heat transfer efficiency (Khawaji et al., 2008). As a result, MSF systems that do not initiate evaporation on heat-exchange surfaces have increased in popularity. As of 2005, the largest MSF desalination facility in operation, with a treatment capacity of 18,927 m^3/h, was located in the United Arab Emirates (Cooley et al., 2006). According to a 2005 inventory (Wangnick and GWI, 2005), MED processes compose

15% of the thermal distillation market and are typically used to meet small municipal or industrial needs at capacities of 47 to 473 m^3/h (Wangnick and GWI, 2005).

B.2.1.4 Membrane Distillation

MD is a thermally driven, membrane-based process (Li and Sirkar, 2005). MD combines membrane technology and evaporation processing in one unit. It involves the transport of water vapor through the pores of hydrophobic membranes via the temperature difference across the membrane. A schematic of the working principle for the MD process is shown in Figure B.3. The temperature difference results in a vapor pressure difference, leading to the transfer of the produced vapor through the hydrophobic membrane to the condensation surface. Membrane materials that have been considered for the MD process include polytetrafluoroethylene, polyvinylidene fluoride, polyethylene, and polypropylene. Typical values for the porosity are 0.06–0.85; for the pore size, 0.2–1.0 μm; and for the thickness, 0.06–0.25 mm. For almost three decades, MD has been considered an alternative to conventional desalination technologies such as MSF and RO. These two techniques involve high energy and high operating pressure, respectively, which result in excessive operating costs. MD offers the attraction of operation at atmospheric pressure and low temperatures (30–90 °C), with the theoretical ability to achieve 100% salt rejection. When MD is coupled with solar energy, geothermal energy, or waste heat, it can achieve cost and energy efficiency. However, the industry has not fully embraced MD for several reasons: low water flux (i.e., productivity) and a shortage of long-term performance data due to the wetting of the hydrophobic microporous membrane (Mathioulakis et al., 2007). Innovative materials that offer microporous membranes with desired porosity, hydrophobicity, low thermal conductivity, and low fouling are essential to bring MD closer to commercialization. Opportunities therefore beckon membrane researchers to improve the flux in the process and increase its durability by fabricating highly permeable superhydrophobic membranes and/or modifying the MD module configurations. The specific energy consumption for MD systems has been reported to be about 43 kWh/m^3 (166 kWh per 1000 gal) of water (Walton et al., 2004).

B.2.1.5 Freezing

Desalination by freezing is categorized as a crystallization processes. Although desalination by freezing has been proposed as a method for several decades, only demonstration projects have been built to date (Qiblawey and Banat, 2008). Freezing is a separation process related to the solid–liquid phase change phenomenon. When the temperature of saline water is reduced to its freezing point, ice crystals of pure water are formed within the salt solution. These ice crystals can be washed and remelted to obtain pure water. In a direct freezing process, the refrigerant is mixed directly with the brine. In an indirect process, the refrigerant is separated from the brine by a heat transfer surface. The process is essentially a conventional compressor-driven refrigeration cycle with the evaporator serving as the ice freezer, and the condenser as the ice melter. Theoretically, freezing has certain advantages compared to distillation. These include a lower theoretical energy requirement, minimal potential for corrosion, and little scaling or precipitation (Qiblawey and Banat, 2008).

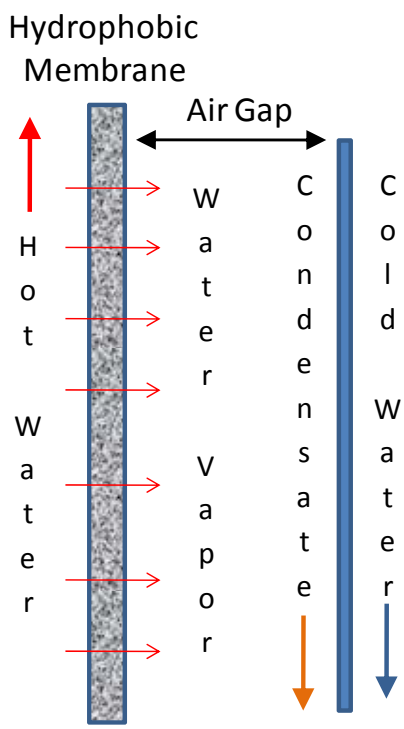

Figure B.3. Schematic of MD process.

B.2.1.6 Hydration

Desalination by hydration involves the formation of gas hydrates. Gas hydrates are crystalline aggregations of hydrogen-bonded water molecules around a central gas molecule (McCormack and Andersen, 2005). These crystalline compounds generally form under moderately elevated pressures, but are known to have freezing points at least as high as 12 °C. The hydration process is similar to a direct contact freezing process utilizing a secondary refrigerant. In the freezing section, gas and water are mixed and the hydrates precipitate. The crystals are physically separated from the remaining brine, washed, and melted. The gas volatilizes away from the water and is recovered for reuse. An advantage of the process is that it could operate at a higher temperature than a conventional freezing process, potentially decreasing the energy requirements of the plant.

B.2.1.7 Reverse Osmosis

Membrane-based desalination processes typically involve the use of RO membranes. In an RO process, the osmotic pressure is overcome by applying an external pressure higher than the osmotic pressure. Thus, water flows in the direction opposed to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration (Wilf and Bartels, 2005). No heating or phase separation is necessary for a RO process. Some of the dissolved minerals and salts may pass through the membrane, but at a much lower rate than water, resulting in the concentration of the remaining solution. The flow of water through the membrane depends on the pressure gradient across the membrane, whereas the flow of dissolved

ions or salts depends on the concentration gradient. As the feed water pressure increases, the water flow increases but the salt flow does not, improving the quality of the product water (assuming that the salt concentration difference across the membrane does not increase). Over time and as technology has advanced, the performance of RO membranes has improved.

Early RO membranes were made from cellulose acetate (Wilf and Bartels, 2005). These membranes offered reasonably high flux rates and salt rejection capabilities, but were not effective outside a narrow range of water quality characteristics. New generation RO membranes are made of polymeric materials (e.g., polyamide) and can offer wider ranges of operating temperature and pH, thus providing more flexibility. However, a substantial degree of physical and chemical pretreatment is still required to reduce fouling of RO membranes (Wilf and Bartels, 2005). Periodic cleaning must also be performed to maintain production capacity through the prevention of scaling and foulant accumulation. RO membrane modules are either spiral-wound or hollow-fiber (Wilf and Bartels, 2005). Hollow-fiber membranes normally push feed water from the outside of the membrane into the center of the fiber. Spiral-wound membranes are assembled from flat-sheet membranes: two membrane sheets are separated by feed water and carrier spacers that provide process water and convey permeate water to a central collector line. An illustration of the spiral wound membrane is shown in Figure B.4. The design configuration and operating characteristics of these pressure vessels depend on feed water quality, treatment objectives, and capacity requirements. Pressure vessels can contain one or many membranes and exist in staged single, parallel, tapered, or numerous other array configurations. The energy consumption for RO processes is primarily due to the power required by the feed pressure pumps, which is directly proportional to the feed water salinity. The specific energy consumption of an RO process for treating seawater is between 2.63 and 4.2 kWh/m^3 (10 and 16 kWh per 1000 gal) (Veerapaneni et al., 2007).

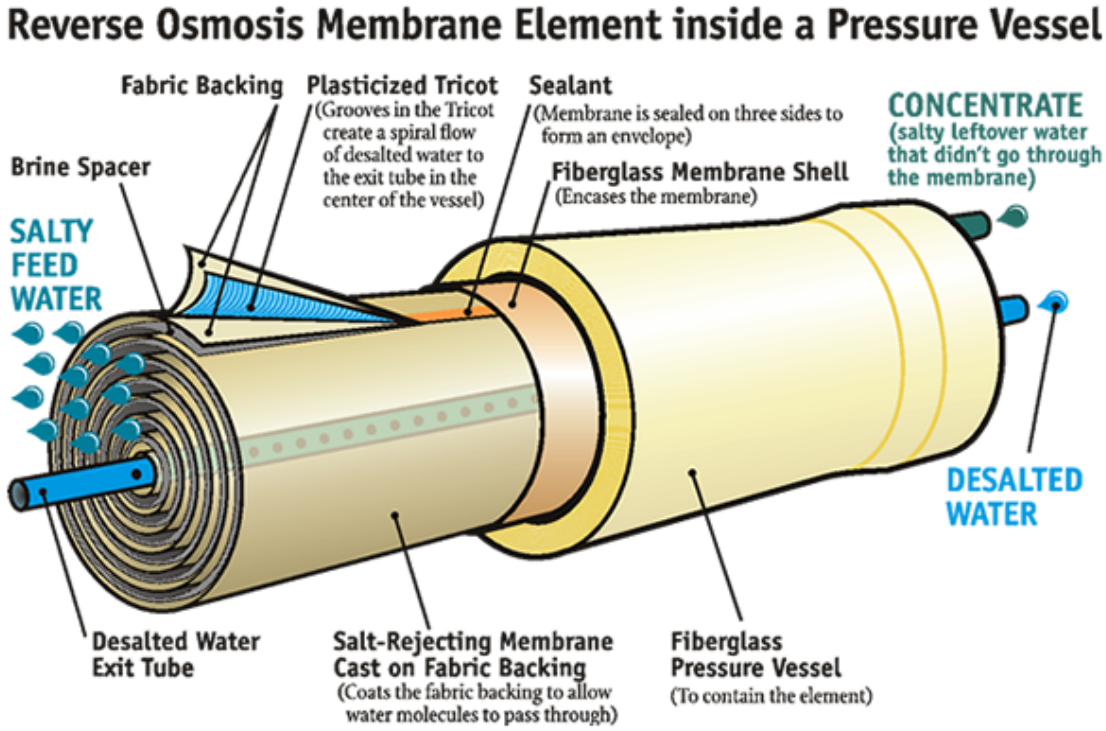

Figure B.4. Schematic of reverse osmosis membrane element(USBR ,2011).

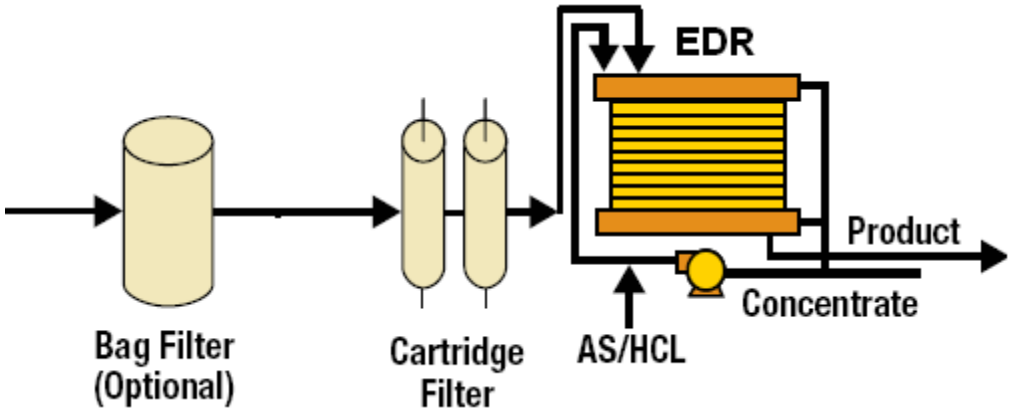

Figure B.5. Schematic of EDR treatment train.

B.2.1.8 Electrodialysis

Electrodialysis (ED), commercially introduced in the 1950s, removes dissolved salts by the application of an electrical potential difference. Positively and negatively charged ions are separated from a solution by oppositely charged electrodes and cation- or anion-permeable membranes (Kalogirou, 2005). Inverters frequently reverse the polarity of the system to prevent scaling. ED systems require less pretreatment than RO systems and have a higher percentage recovery than thermal distillation systems (i.e., produce more product water and less brine). However, energy requirements of the ED process are directly proportional to the salinity of the feed water. As a result, ED is commonly used to treat brackish waters with lower dissolved solids concentrations (Mathioulakis et al., 2007). The development of a modification to the ED system–electrodialysis reversal (EDR)–has further increased the performance of these systems. An illustration of the EDR process is shown in Figure B.5. EDR systems are functionally similar to the ED process but can operate on more turbid feed water, have higher water recovery than RO, and are less prone to biofouling than RO systems. Nevertheless, energy requirements still hinder the widespread acceptance of ED or EDR for the purification of seawater. The specific energy consumption of the EDR process for brackish water has been reported to be 1.26 kWh/m^3 (4.8 kWh per 1000 gal) (Chang et al., 2008).

B.2.1.9 Dewvaporation

Dewvaporation is a specific process of humidification–dehumidification desalination, which uses air as a carrier-gas to evaporate water from saline feeds and form pure condensate at constant atmospheric pressure (He and Yan, 2009). The heat needed for evaporation is supplied by the heat released by dew condensation on the opposite side of a heat transfer wall. Because external heat is needed to establish a temperature difference across the wall, and because the temperature of the external heat is versatile, the external heat source can be from waste heat, from solar collectors, or from fuel combustion. The unit is constructed out of thin water wettable plastics and operated at atmospheric pressure. The standard dewvaporation continuous contacting tower is a relatively new, nontraditional, and innovative heat–driven process using air as a carrier gas and remaining at atmospheric pressure throughout the device. The external heat source can be low-temperature solar, waste heat, or combustible fuels. In comparison to desalination using conventional techniques, a dewvaporation process utilizing waste heat can provide reduced energy consumption.

B.3 Comparison of Desalination Technologies

A comparison of common desalination technologies is presented in Table B.1. The advantages of membrane processes over thermal processes include lower capital cost and energy requirements, lower footprint and higher space/production ratio, higher recovery ratio, minimal interruption of operation during maintenance, less vulnerability to corrosion, and better rejection properties for microbial contaminants. The advantages of thermal processes over membrane processes include a proven and established technology, higher quality of product water, and less impact from feed water quality changes. The higher product water quality with thermal desalination technologies can also be used to achieve higher feed and permeate water blend ratios, thereby reducing the required capacity of the particular desalination technology.

Table B.1. Comparison of Common Desalination Techniques (Ettouney et al., 1999)

Process	Recovery	Permeate TDS	Advantages	Disadvantages
RO	30–60% recovery with single pass Higher recoveries possible with multiple passes	< 500 mg/L for seawater < 200 mg/L for brackish water	Lower energy consumption Relatively lower investment cost Modular design Removal of contaminants other than salts Simple operation and fast start-up Maintenance does not require entire plant shutdown High space/production capacity	Higher costs for chemical and membrane replacement Adequate pretreatment a necessity Membranes susceptible to biofouling Minimum membrane life expectancy around 5–7 years
ED	85–94% recovery possible.	140 - 600 mg/L	Energy usage proportional to salts removed and not volume-treated Higher membrane life of 7–10 years Operational at low to moderate pressures	Only suitable for feed water up to 12,000 mg/L TDS Bacterial contaminants not removed Periodic cleaning of membranes required
MSF	25–50% recovery in high–temperature recyclable MSF plant.	< 50 mg/L	Large capacity designs Proven, reliable technology with long operating life Reduced scaling Minimal pretreatment required Plant process and cost independent of salinity level Heat energy can be sourced by combining with power generation	Large capital investment required Energy-intensive process Large footprint requirement Maintenance requires entire plant shutdown Recovery ratio is low High level of technical knowledge required
MED	Up to 65% recovery is possible.	<10 mg/L	Large capacity designs	High energy consumption

Process	Recovery	Permeate TDS	Advantages	Disadvantages
VC	50% recovery possible.	<10 mg/L	Minimal pretreatment required Reliable process with minimal requirements for operational staff Heat energy can be sourced by combining with power generation . Very high-quality product water Developed process with low consumption of chemicals Relatively low energy demand . Lower temperature requirements reduce potential for scale and corrosion . Relatively lower capital and operating costs Portable designs allow flexibility	High capital and operational cost High quality materials required, as process is susceptible to corrosion Product water requires cooling and blending prior to being used for potable water need. Start-up requires auxiliary heating source to generate vapor Limited to small plants Compressor needs higher levels of maintenance

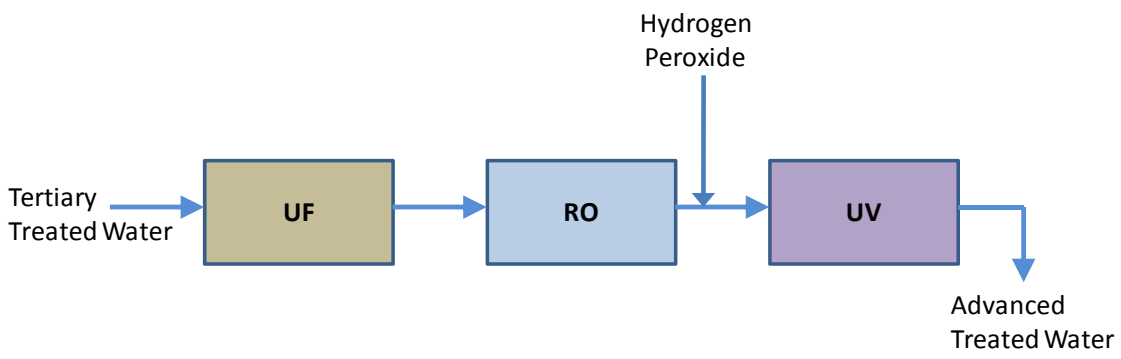

Figure B.6. Illustration of an advanced water treatment system (MWH, 2006).

B.4 Water Reuse Technology Background

Water reuse and advanced water treatment technologies consist of a combination of membrane and disinfection technologies to produce water for either indirect or direct potable reuse. An example of an advanced water treatment process used for producing water for indirect potable reuse in San Diego is shown in Figure B.6. The system uses a combination of UF and RO to remove suspended solids, organics, and TDS from the tertiary treated wastewater stream. The permeate stream from the RO process is further treated using a combination of UV and hydrogen peroxide. Advanced oxidation is necessary to achieve additional reduction of *N*-nitrosodimethylamine (a nitrogenous disinfection by-product) beyond what can be accomplished using membranes.

B.4.1 Low-Pressure Membrane Systems

In an advanced water treatment system, low-pressure membranes are typically used as pretreatment. Low-pressure membranes generally employ either MF or UF. MF membranes have pore sizes in the range of 0.05 to 5 µm, whereas UF membrane have slightly smaller pores ranging from 0.002 to 0.1 µm (Jacangelo and Buckley, 1996). MF and UF membranes may be used in either a spiral-wound, tubular, or hollow-fiber element design, with hollow-fiber being the most prevalent for municipal applications (Chang et al., 2008). The permeate water flux for low-pressure membranes is dependent on site-specific water turbidity, pump sizing, and acceptable levels of transmembrane pressure (Chang et al., 2008). A typical process schematic for low-pressure membranes is shown in Figure B.7. Raw water is first passed through a prescreen to remove large particles that may damage the membrane fibers or pumps. Based on the system configuration, a feed pump supplies water to the membrane bank and supplies the driving pressure through the membrane, or there is a vacuum pump that draws the water through the membranes, which are submerged in a tank. The permeate is stored in a finished water storage tank from which it can be sent to additional treatment processes in water reuse applications. Air scouring may be employed during the backwash to further clean the membranes. Some systems are also operated in cross-flow operation mode (Chang et al., 2008).

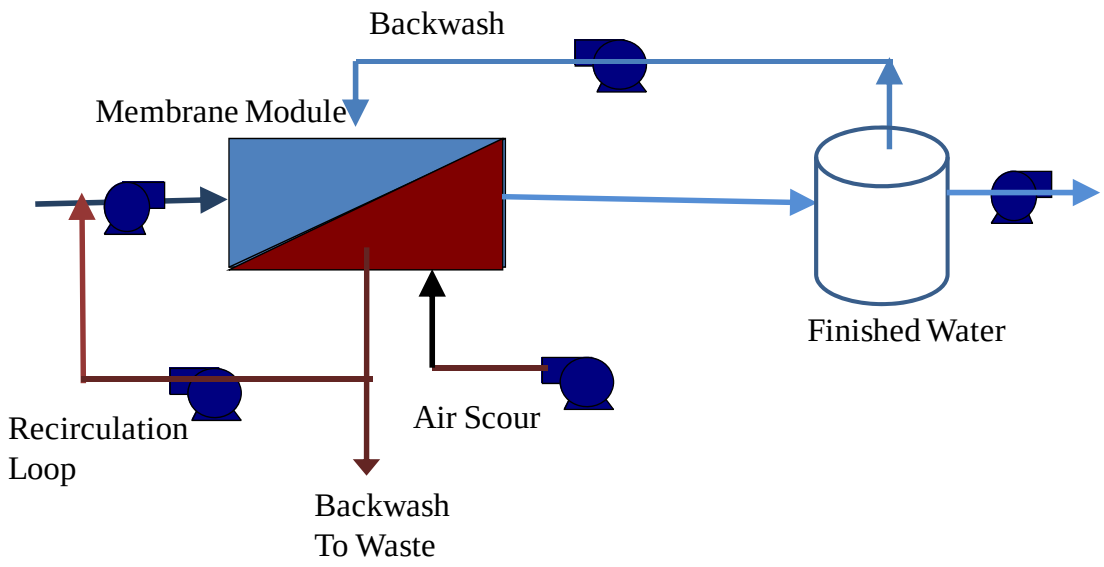

Figure B.7. General process schematic for low-pressure water treatment membrane systems (Chang et al., 2008).

MBR are specialized low-pressure membranes modified for municipal wastewater treatment. In an MBR process, a combination of low-pressure membrane filtration and the activated sludge process is involved. A schematic of the MBR process is shown in Figure B.8. The principal difference from MF and UF membranes is that MBRs require aeration during the filtration process to reduce the amount of fouling caused by the high concentration of suspended solids typical in municipal wastewaters. In an MBR process, aeration and anoxic zones are typically used ahead of the membrane process in order to achieve higher nutrient removal. The effluent from MBRs can be further treated using RO, followed by disinfection using UV and hydrogen peroxide.

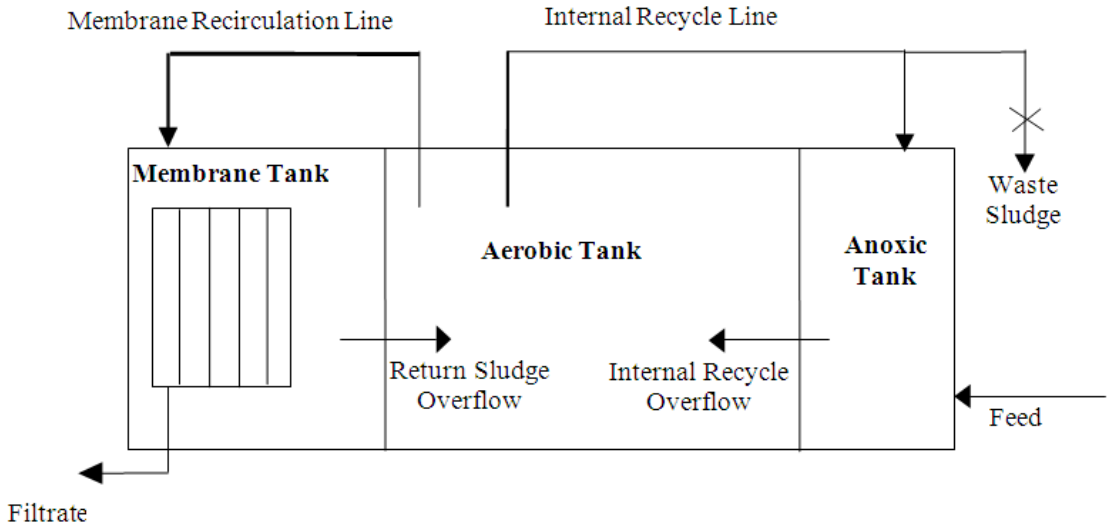

Figure B.8. General process flow schematic of MBR process.

B.4.2 UV disinfection

An UV disinfection system transfers electromagnetic energy from a mercury arc lamp to an organism's genetic material (DNA and RNA). When UV radiation penetrates the cell wall of an organism, it destroys the cell's ability to reproduce. The effectiveness of UV disinfection depends on the characteristics of the wastewater, the intensity of the UV radiation, the amount of time the microorganisms are exposed to the radiation, and the UV reactor configuration (Chang et al., 2008).

The main components of a UV disinfection system are mercury arc lamps, a reactor, and ballasts. The source of UV radiation is either low-pressure or medium-pressure mercury arc lamps with low or high intensity. The optimum wavelength to effectively inactivate microorganisms is in the range from 250 to 270 nm. The intensity of the radiation emitted by the lamp dissipates as the distance from the lamp increases. Low-pressure lamps emit essentially monochromatic light at a wavelength of 253.7 nm. Medium-pressure lamps are often used in large facilities. They have approximately 15 to 20 times the germicidal UV intensity of low-pressure lamps. The medium-pressure lamp disinfects faster and has greater penetration capability because of its higher intensity. However, these lamps operate at higher temperatures with significantly higher energy consumption. Low-pressure UV systems are generally 40 to 50% more energy-efficient than medium-pressure systems, but the large number of low-pressure lamps required may result in higher maintenance and capital costs.

B.4.3 Ozonation

Advanced water treatment can also be accomplished using ozone as part of the treatment process (Chang et al., 2008). The ozonation process includes four steps: feed-gas preparation, ozone generation, ozone contact, and off-gas treatment. A typical process layout for ozonation in water treatment is shown in Figure B.9. The feed gas is typically passed through a desiccator to reduce the gas water content and achieve minimum moisture content of the feed gas. Ozone is produced by applying a high-voltage alternating current (6–20 kVAC) across a dielectric discharge gap that contains the feed gas. On-site generation is required, as ozone is highly unstable. The feed gas stream typically contains approximately 0.5 to 3% weight of ozone. The ozone gas stream is diffused into the feed water using a downflow contact basin. The contact basin may be a diffused bubbler, a mechanical agitation system, a packed tower, or a venture mixer. Off-gas in the contactor is collected and sent to a heat catalyst or activated carbon unit, which reduces the ozone to oxygen and discharges it to the atmosphere (Chang et al., 2008).

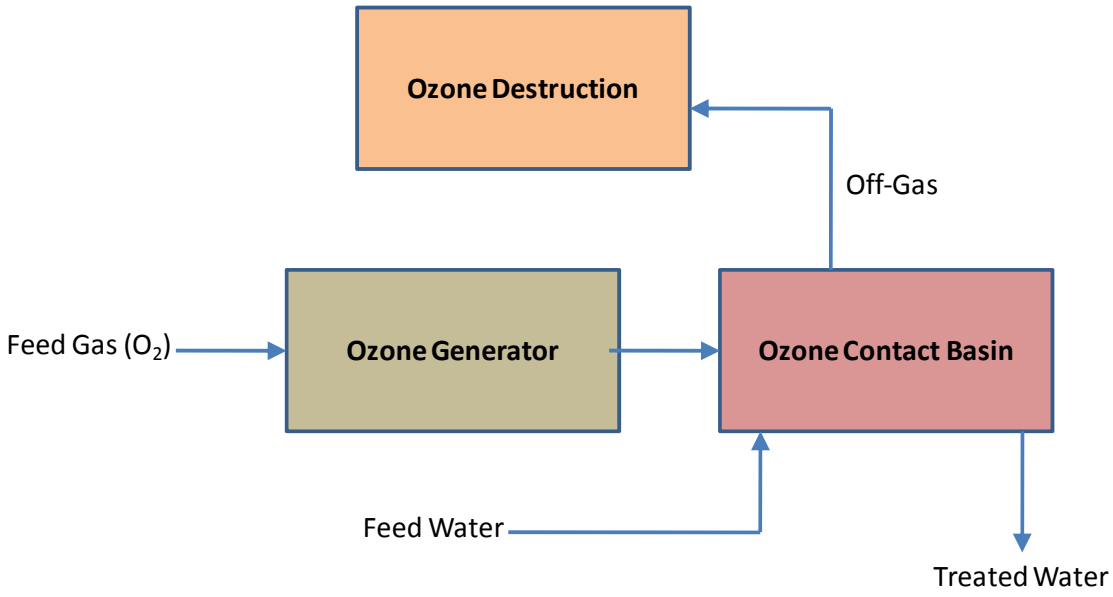

Figure B.9. General process schematic of ozonation water treatment system.

B.5 Overview of Process Energy

B.5.1 Energy consumption of desalination processes

Though several technologies are currently available for desalination, the use of reverse osmosis membranes is predominant in many regions of the world. In the United States, more than 69% of the desalination capacity utilizes RO membranes for desalination (Greenlee et al., 2009). Both MSF and VC processes have significantly higher energy consumption than the RO process. Although the energy consumption of MED processes can be comparable to that of RO, the capital costs can be substantially higher for the MED process (Veerapaneni et al., 2007). Hence, desalination using RO membranes is gaining acceptance as the predominant desalination process. Moreover, improvements to RO membrane material and energy-recovery devices in the past decade have significantly improved the energy efficiency of RO desalination. For these reasons, the use of RO is gaining importance in treating high-salinity feed water. As discussed previously, the largest component of power usage is due to the high-pressure pumps required to feed the water for the first pass of the RO process. More than 33% of the cost of seawater desalination is attributed to electric power requirements. Higher recovery increases feed pressure requirements and hence the energy consumption. The optimum recovery based on energy consumption is between 35 and 45%. The optimum recovery based on life-cycle cost is between 42 and 45% (Long, 2008). Hence, reducing energy consumption is critical in lowering the cost of desalination.

B.5.2 Energy consumption of advanced water treatment processes

B.5.2.1 Low-Pressure Membranes

When low-pressure membranes are used for pretreatment for RO, the components that consume the largest fraction of energy include the feed/vacuum pump, backwash pump, air scour blower, and recirculation pump (Chang et al., 2008). Use of heaters for temperature control of chemical cleaning solutions can also consume significant amounts of energy. Thus, membrane fouling is a

significant determinant of energy consumption in MF and UF processes. As membrane permeability decreases because of fouling, higher pressure is required to maintain a constant permeate flow. Energy consumption by the backwash and air scour systems will depend on the frequency of backwash/air scouring and the volume of backwash water that is used (Chang et al., 2008).

Energy consumption in MBRs is largely determined by the pressure required to transport water across the membrane, which is typically done using vacuum pumps, and the aeration systems (Cheng et al., 2008). Energy in MBR systems is also consumed by support processes, such as the backwashing and clean-in-place (CIP) systems. The process air blowers and air scour blowers consume the largest fraction of the total MBR energy requirement (Chang et al., 2008). The process pumps comprise the vacuum pumps, the backflushing pumps, and the foam pumping system. The aeration sequence used in MBR systems has been reported to dramatically impact the energy usage. For continuous aeration systems, up to 50% of the total energy can be attributed to aeration. Cyclic aeration has been reported to reduce the aeration power requirement by up to 70% (Chang et al., 2008). Energy consumption of MBR processes has been estimated to be on average 0.44 kWh/m^3 (1.7 kWh per 1000 gal) of water treated (Pellegrin and Kinnear, 2010).

B.5.2.2 Ultraviolet Disinfection

When UV systems are used for post-treatment, the principal energy consumer is the lamps that generate the UV light (Chang et al., 2008). NYSERDA investigated the use of three UV technologies for wastewater treatment (NYSERDA, 2004). The technologies tested were low pressure–low intensity, low pressure–high intensity, and medium pressure–high intensity. These technologies were investigated at pilot scale under a variety of UV doses and flow rates. To meet a fecal coliform effluent limit of 200 MPN (most probable number)/100 ml, a fecal log inactivation of 2.7–2.9 was required. The inactivation level required UV doses of 26, 30, and 32 mW-s/cm^2 for low pressure–low intensity, low pressure–high intensity, and medium pressure–high intensity, respectively. It has been reported that UV disinfection increases energy consumption by 70 to 100 kWh/MG relative to that needed by conventional chlorination processes (EPRI, 1997). The NYSERDA study also compared the power requirements for the three pilot plants with the amount of power needed by a chlorination/dechlorination facility using hypochlorite and sodium bisulfate to treat the same quantity of water.

The energy consumption of low- and medium- pressure lamps used to disinfect biologically treated wastewater to comply with an effluent limit of 200 fecal coliform per 100 mL is summarized in Table B.2. Compared to a chlorination/dechlorination facility, which uses 6 kW, the UV systems have power usage of 60 kW (low pressure–low intensity), 45 kW (low pressure–high intensity), and 190 kW (medium pressure–high intensity) (NYSERDA, 2004). The study concluded that low pressure–low intensity UV lamps would not be cost-effective for an application with high flow rates.

Table B.2. Energy Consumption of UV Lamps (NYSERDA, 2004)

Variable	Low Pressure–Low Intensity	Low Pressure–High Intensity	Medium Pressure–High Intensity
Emission wavelength	254 nm	Broad spectrum	Broad spectrum
Power draw (W)	88	250	1000–15,000
Power use (kWh/MG)	3.2–4.8	—	6.8–15
Typical cost ($/lamp)	45	185	225

B.5.2.3 Ozonation

The major energy consumption components for ozonation systems are feed-gas treatment, ozone generator, cooling water pumps for the ozone generator, and ozone destruction unit (Chang et al., 2008). The primary energy consumption is due to the ozone generator. The ozone generator consumes energy by the production of voltage and the pumping of cooling water through the generator. The ozone diffuser requires energy for pumping the ozone-rich gas into the contact basin. Energy consumption associated with the ozone generator tends to increase with increasing ozone generation rate, but the energy required for the auxiliary systems remains relatively fixed regardless of the ozone generation rate. The energy consumption of ozonation systems used for disinfection can range from 0.005 to 0.013 kWh/m^3 (0.02 to 0.05 kWh per 1000 gal), 0.015 to 0.021 kWh/m^3 (0.06 to 0.08 kWh per 1000 gal), and 0.028 to 0.04 kWh/m^3 (0.11 to 0.16 kWh per 1000 gal) when liquid oxygen, vacuum pressure swing adsorption, and ambient air are used as feed (Chang et al., 2008).

B.5.3 Energy Minimization for Membrane Desalination Systems

Because the use of RO membranes is the predominant method of desalination, especially in the United States, energy minimization for desalination systems will be focused on membrane processes. Operating methods or process components used to reduce the overall energy requirements in RO desalination processes are described in this section. The cost of desalinating high-salinity water has decreased from about \$1.94/m^3 of water in 1998 to about \$0.5/m^3 of water currently. The key factor in economic improvement is due to advances in the process and membrane technology (Wilf and Bartels, 2005). In addition to the utilization of renewable energy resources, other factors influential in energy minimization and costs can be classified as:

- Enhanced RO system design
- High-efficiency pumping
- Energy recovery
- Advanced membrane material
- Application of innovative technologies

Each of these factors will be described in detail in the following sub-sections.

B.5.3.1 Enhanced Reverse Osmosis System Design

Design and configuration of the membrane unit can have a significant effect on the performance and economics of the RO plant (Wilf and Bartels, 2005). In the past, membrane units for feed water with high salinity were usually configured as two stages, with six elements per pressure vessel. A two-stage system results in a high feed and concentrate flow, reducing concentration polarization. Because of the higher feed flow, greater feed pressure is required to compensate for the increased pressure drop across the RO train. Design efforts to reduce power consumption have resulted in the use of single-stage configurations for high-salinity feed water applications. In some cases, seven (or eight) elements per pressure vessel are currently being used (Wilf and Bartels, 2005). The reduction in pressure drop from using a single stage instead of a two-stage system can result in a 2.5% lower power requirement (Wilf and Bartels, 2005). The use of larger-diameter elements (16-in. and 18-in.) instead of the typical 8-in. element has also been reported to reduce the capital cost by as much as 10% by minimizing footprint requirements. The

use of 18-in. elements has been reported to produce seven times as much permeate as the use of 8-in. elements (van Gottberg et al., 2005).

Employing seven (or eight) elements per pressure vessel can lead to an uneven flux distribution with the lead elements when compared to the tail elements. Flux is a critical design parameter that determines the membrane area required to produce a target permeate flow rate (Veerapaneni et al., 2007). A higher design flux can lower the capital cost because fewer membrane elements are required. However, higher flux can also lead to higher fouling rates and more frequent cleaning intervals, which ultimately result in increased operating costs. Because energy consumption contributes significantly to the cost of desalinated water, an optimum flux must be balanced between capital and operating costs. Studies have shown that reduced capital cost due to higher flux rates does not necessarily lower treated water costs (Veerapaneni et al., 2007).

Another innovative design to reduce the pressure drop involved the use of a pressure vessel with a center port design (van Paassen et al., 2005). In this configuration, feed water enters the pressure vessel through two feed ports on each end of the pressure vessel in the first stage. The concentrate is collected through a middle port and flows to the middle port of a pressure vessel in the second stage. Thus, the flow path is reduced by half. In the center port design configuration, although the membrane unit has eight elements per pressure vessel, the flow path length is reduced to four elements per stage. Utilization of the center port pressure vessel results in lower feed pressure because of a lower pressure drop. A 15% reduction in the feed pressure has been reported from using the center port design rather than a conventional side port design (Wilf and Hudkins, 2010). The disadvantage of the center port design is the concern of scaling due to excessive concentration polarization. Thus, pilot testing is required before the implementation of the center port design to determine the influence of varying water quality on feed water recovery.

Optimization of energy consumption for RO treating high-salinity feed water has also been performed using a two-stage hybrid system with concentrate staging (Veerapaneni et al., 2005). The first stage consists of high-rejection brackish water membrane elements or high-permeability seawater membrane elements. The second stage consists of standard seawater elements. Using a two-stage system with brackish/low-pressure seawater membranes in the first stage requires lower feed pressure requirements because of lower membrane resistance (Veerapaneni, 2007). As most of the permeate is produced in the first stage by the use of high-permeability membranes, the pressure of only a small fraction of the remaining flow is boosted, resulting in significant energy savings. To reduce energy consumption, a two-pass nanofiltration system has been used by the Long Beach Water Department. Energy consumption was reduced by more than 5% when brackish water RO elements were used in combination with seawater RO elements. More than a 2% reduction in energy consumption was reported when two-pass nanofiltration was used (Long, 2008).

B.5.3.2 High-Efficiency Pumping

As discussed earlier, a major part of energy consumption is due to feed water pumping requirements. Because it is difficult to scale up all the process components from pilot-scale to full-scale applications, scale-up of pumps across a range of flows is a challenge. To achieve the highest possible efficiency, a typical pump would require the specific speed to be within a specified range for optimal efficiency (Veerapaneni, 2007). The use of high-speed and high-flow pumps at lower total dynamic head would result in optimal speed for highest efficiency. For large RO plants, the flow can be increased by centralized feed pumps that feed either larger skids or several smaller skids (Wilf and Bartels, 2005). Models of water-lubricated axial-piston pumps

(APP) are claimed to have high mechanical reliability and high efficiency in delivering pressures in the range needed for high-salinity feed water RO applications (MWH, 2007). To accommodate variability of feed pressure with time (due to salinity and temperature fluctuations), without the necessity to throttle high-pressure pumps or energy recovery devices, a VFD is incorporated into the electric motor unit that drives the high-pressure pump (Wilf and Bartels, 2005).

Numerous factors contribute to inefficient pumping. Performing a pump test and analyzing the test curves will help in determining the course of actions that can be taken to improve efficiency (Brandt et al., 2010; Kaya et al., 2008). Some common improvements include development of an optimum pump operational plan based on pump performance characteristics and system head requirements, replacement of pumps with energy-efficient pumps, drives, and motors, replacement of worn-out pump components, replacement of worn-out valves, trimming pump impellers, and adding VFDs.

The pump manufacturer's O&M manual provides maintenance intervals, guidelines, and procedures for pumping equipment. Pump components such as bearings, wearing rings, impellers, and mechanical seals must be checked and replaced as recommended in the O&M manual. Factory-preset clearances and tolerances must be observed and maintained. Worn-out or misaligned components affect pump performance and efficiency. Restoring pump clearances, repairing worn impeller and casing water passages, and applying new coatings to pump casing volutes and impellers has been proven to reduce water frictional losses (Brandt et al., 2010; Kaya et al., 2008). Coatings, such as Fluiglide, have recently been developed to reduce energy consumption of pumps (Corrocoat, 2011). Fluiglide is an advanced coating system that increases the overall efficiency levels of pumps and provides an effective corrosion barrier, preventing early fall-off in performance due to nodular growth and surface corrosion. The application of Fluiglide coatings to surfaces reduces the roughness amplitude, thereby reducing frictional losses.

For motors, by increasing the cross section of the copper conductors that are used in the motor winding, the primary I^2R losses can be decreased (Kaya et al., 2008). Iron core loss with the decrease of flux density can be limited by increasing the neck of the stator core (Kaya et al., 2008). These losses can also be further decreased by decreasing the thickness of the panels and using good-quality alloys (Kaya et al., 2008). In one study at a plant, existing pump efficiencies were 46–55%. After low–efficiency pumps were replaced with high-efficiency pumps, the pump efficiency was 60 – 71% (Kaya et al., 2008).

Pumping efficiency can also be improved by selection of the correct motor, which would include matching the horsepower output rating to the load, matching the motor utilization voltage to the provided systems voltage, matching the speed and torque rating of the motor and drive to the requirements of load speed and torque, and matching motor and drive requirements, including using inverter-rated motors with VFDs (Kaya et al., 2008). For applications involving variable flow, where the frictional pipe and valve losses are significant compared to the static head requirement, VFDs should be considered, especially if throttle valves, pressure control valves, or bypass valves are used in the system.

Electrical distribution and power quality issues should be looked at, including voltage problems (outages, sags, swells, overvoltage, undervoltage, phase voltage unbalance, transients, and harmonics), power factor, and electromagnetic interference (Kaya et al., 2008). These items may reduce motor efficiency and damage equipment in some severe cases. There are many potential solutions to these problems, including reduced-voltage starters (soft starters), surge arresters and

surge protective devices (previously identified as transient voltage surge suppressors), VFDs, line reactors (input and output), filters, isolation transformers, and uninterruptable power supplies (Kaya et al., 2008).

B.5.3.3 Energy Recovery

Recovery of energy is crucial in making desalination of high salinity water economically feasible. Energy consumption for RO desalination processes can be reduced by using ERDs. The energy of the RO concentrate can be recovered by passing the concentrate stream through ERDs. The fraction of power recovered by the ERD depends on the type and efficiency of the equipment used. Four broad categories of ERDs are available, as follows:

- Pelton wheel turbine (PWT)
- reverse-running turbine pump (RRTP)
- turbo-booster pump (TBP)
- pressure or work exchanger (PWE) systems

The PWT, RRTP, and TBP are centrifugal types, whereas the PWE systems are isobaric. The centrifugal ERDs are limited in capacity and are usually optimized for narrow flow and pressure operating conditions (Stover, 2007). Isobaric ERDs achieve higher efficiency than centrifugal ERDs. Descriptions of each system are presented in the following.

Pelton Wheel Turbine (PWT): In a PWT, the RO concentrate stream is guided through a nozzle and made to impinge on turbine blades, which are of bucket shape (Stover, 2004). Pressurized water ejected through one or more nozzles is directed against a series of spoon-shaped buckets mounted around the edge of a wheel. Each bucket reverses the flow of water, leaving it with diminished energy, and the resulting impulse spins the turbine. The buckets are mounted in pairs to keep the forces on the wheel balanced as well as to ensure smooth, efficient momentum transfer from the fluid jet to the wheel. The wheel is mounted on the high-pressure pump shaft, which together with a motor drives the pump that pressurizes the RO system. Thus, the energy content of the high-pressure concentrate stream is usefully utilized to recover the energy. A Pelton wheel can be mechanically coupled directly to the RO feed water pump's shaft to reduce the work needed by the pump's motor. Pelton wheel turbines have few moving parts, are easy to maintain, and generally have high reliability (MWH, 2007). Efficiency of commercial Pelton wheels can reach 90%. The concentrate stream exiting the Pelton wheel is at atmospheric pressure and has to be able to freely flow to the discharge, or has to be pumped.

Reverse-Running Turbine Pump (RRTP): Two basic categories of the RRTP exist. The first category is a mechanically coupled type and the second is a hydroelectric submersible generator (MWH, 2007). A RRTP can be mechanically connected to the RO feed pressure pump and motor's shaft to allow unlading of the motor's work, with a resulting reduction in the horsepower required to drive the membrane pump. The submersible generator is a small-scale version of a hydroelectric plant. Induction generator and turbine pump impeller stages are installed inside a section of pipe, where a high-pressure RO concentrate stream flows through and rotates the RRTP and generator to produce electricity. Electricity produced by the submersible generator is then fed to a generator control and protection panel. The electricity generated can be used for operation of the RO plant or can be exported to a local electricity grid. The RRTP is not suitable for low flow range due to poor efficiency (Mirza, 2008).

The overall efficiency of the mechanically coupled RRTP is in the 75% to 85% range. For the submersible generator type, the overall efficiency is in the 62% to 75% range. The RRTP devices can operate with a liquid backpressure and do not need the discharge from the device to free-fall to a sump or chamber. The RRTP device can consume more power when system conditions are changed. These devices were found to be difficult to use and quickly fell out of favor (Mirza, 2008).

Turbo-Booster Pump (TBP): The turbo-booster has a Francis wheel turbine coupled to a single-stage pump by a shaft. The TBP is a free-running pump and turbine combination. A high-pressure RO concentrate stream is passed through the turbine end of the device, which rotates the pump shaft and provides energy needed for the pump to boost the pressure of the feed water RO stream (Lozier et al., 1989). Thus, the energy required for the high-pressure RO feed pump is reduced. The TBP is a rotary machine with only a few moving parts and does not require external lubrication. It has no electrical or pneumatic components. Hence, the TBP requires low maintenance. It is free to operate over a wide range of speeds and is not limited to the pump speed (Oklejas et al., 2005).

The device is relatively compact in size and has low weight compared to other ERDs. Because the TBP can operate with back pressure, the discharge stream from the device can be pressurized and transferred without repumping. The efficiency of the TBP ranges from 55% to 60%. The TBP's recovery of energy is affected by changes in the RO process flow rates caused by water temperature and feed water recovery changes. The TBP is typically used in smaller-capacity RO installations (MWH, 2007).

Pressure or Work Exchanger (PWE) Systems: The pressure or work exchanger (PWE) is a positive-displacement-type ERD. The PWE transfers the hydraulic energy of the pressurized RO concentrate stream to the RO feed water stream (Stover, 2007; Geisler et al., 1999). PWE systems can be categorized into two types; those that provide a physical barrier (piston) between the RO concentrate stream and feed side of the system, such as dual work exchanger energy recovery (DWEER), and those without a physical barrier, such as the pressure exchanger (PX) (Cameron and Clemente, 2008). A schematic of the DWEER installation is available from Flowserve Inc. (Flowserve, 2011). A typical process flow train of DWEER pressure exchangers installed in a seawater desalination plant is shown in Figure B.10. The system is based on moving pistons in cylinders. The high-pressure RO concentrate stream is directed to a work exchanger filled with low-pressure RO feed water. The system pressurizes the feed water to brine pressure. Critical elements of the system include moving parts and valves. Although the piston and cylinder arrangement is well suited for a wide range of water viscosities and densities, the system requires a large footprint (Mirza, 2008).

The working principle of a pressure exchanger (PX) is provided by ERI Inc. (ERI, 2011). The PX device is a positive displacement isobaric energy recovery device. The device consists of a ceramic cartridge with a feed water end cover, a rotor, a sleeve, and a concentrate end cover (Cameron and Clemente, 2008). The rotor contains axial ducts arranged in a circle around a center tension rod. The PX device directly pressurizes the feed water. Therefore, no transformational losses occur in the device and hence it has higher efficiency. The feed water and concentrate stream come into direct contact in the rotor, but mixing between the streams is limited by a water barrier that exists in the duct.

Although individual PXs have limited flow rates, higher capacity can be achieved by arranging several devices in series. Recently, the world's largest rotary isobaric energy recovery device for high-salinity RO applications was installed in Maspalomas, Spain (Stover, 2007). The device

(Titan 1200) can handle five times the flow of a standard PX (PX-180 and PX-220 from ERI Inc). The PX device has also been proven to lower costs for brackish water applications (MacHarg and McClellan, 2004). The PX device has been associated with very high noise levels requiring a sound abatement enclosure (Mirza, 2008). Another disadvantage of the PX device is the degree of mixing between the feed water and the concentrate stream. A mixing feed salinity between 1.5% and 3.0% results in an increase of required feed pressure for the RO system (Stover, 2004).

A comparison of the various energy recovery devices described is shown in Table B.3. Although all the described devices are proven technologies, certain devices (such as PWE) have higher efficiency than the other devices mentioned. Because PWE has the highest efficiency among the other ERDs, numerous RO desalination plants use this technology for energy recovery. Pressure exchangers from ERI alone have been installed in more than 400 RO installations worldwide (Cameron and Clemente, 2008). The Ghalilah SWRO plant utilizes a PX device from ERI to save energy and reduce power consumption (Stover et al., 2005). The PX device efficiency exceeds 95% at this location, with low mixing and low noise. Some of the other PX installations are in the Caribbean, China, Middle East, and Singapore (Cameron and Clemente, 2008; Veerapaneni et al., 2007). The 5,678 m^3/h (36 MGD) SWRO plant in Tuas, Singapore is regarded as the world's most efficient full-scale plant (Kiang et al., 2005).

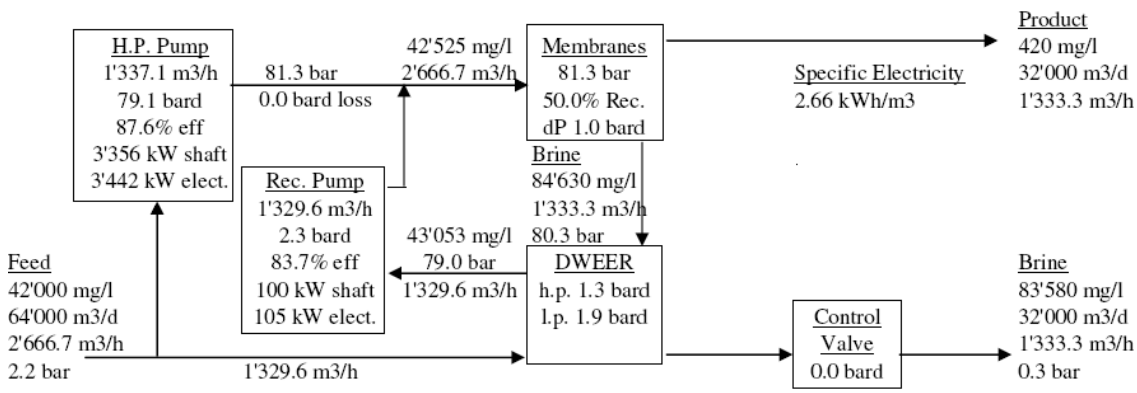

Figure B.10. Typical process schematic of Calder DWEER pressure exchanger installed for seawater desalination.

Table B.3. Comparison of Energy Recovery Devices (MWH, 2007)

Criterion/Device	Pelton Wheel Turbine (PWT)	Reverse-Running Turbine Pump (RRTP)	Turbo-Booster Pump (TBP)	Pressure or Work Exchanger (PWE)
Commercial availability	Yes	Yes	Yes	Yes
Proven technology for high-salinity applications	Yes	Yes	Yes	Yes
Potential energy savings (relative to each other)	Medium	Low to medium	Low	High
Capital cost (relative to each other)	Low to medium	Low to medium	Low	High
O&M cost (relative to each other)	Low	Low	Low	High for multiple valve systems Medium for multiported single-valve systems Low to medium for valveless multiport rotating cylinder system.
Efficiency (relative to each other)	Medium (84% to 90%)	Mechanically coupled RRTP = low to medium (75% to 85%) Submersible generator = low to medium (62% to 75%)	Low (55% to 60%)	High (95% to 97%)
Efficiency curve	Varies	Varies	Slopes downward at low flows	Flat
Efficiency under changing process conditions (effect of deviation from design point)	Efficiency decreases when flow rate changes from design point	Efficiency decreases when flow rate changes from design point	Efficiency decreases when flow rate changes from design point.	Moderate impact on performance, efficiency maintained over a broad operating range

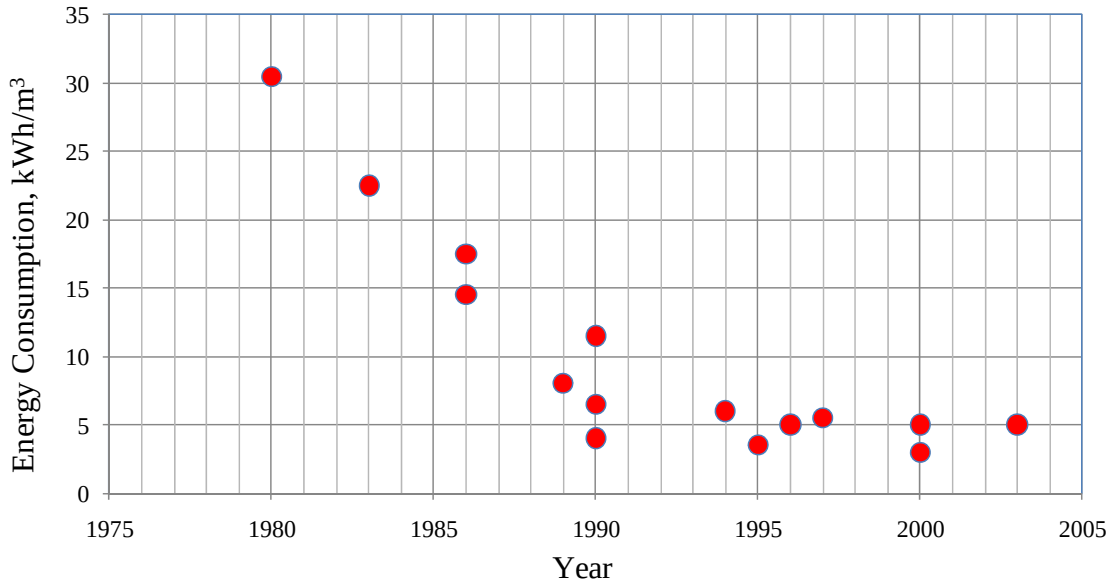

Figure B.11. Energy requirement for seawater RO processes (Chang et al., 2008).

B.5.3.4 Advanced Membrane Material

Significant improvements in the salt rejection capacity and permeability of the RO membranes for treating high-salinity feed waters have been achieved in recent years. The specific energy consumption for seawater RO membranes since the early 1980s is plotted in Figure B.11. In 1980, seawater RO systems consumed more than 30 kWh/m^3 (113 kWh per 1000 gal) of water produced. Today, seawater RO systems consume on average only 3.5 kWh/m^3 (13 kWh per 1000 gal) (Chang et al., 2008). New-generation RO membranes offer reduced feed pressure requirements while maintaining rejection. Research is also being performed to minimize energy losses and improve flow distribution within the membrane element to maximize the use of membrane area. Today's high-productivity membrane elements are designed with two features that result in more fresh water per membrane element: higher surface area and denser membrane packing (Voutchkov, 2007).

Nanocomposite membranes: New focus is also on developing new-generation RO membranes (Hoek and Ghosh, 2009). New-generation thin film composite RO membranes are made by combining zeolite nanoparticles dispersed within a traditional polyamide thin film (Jeong et al., 2007). An illustration of the nanocomposite membrane structure is available t NanoH2O's website (NanoH20, 2011). The zeolite nanoparticles are dispersed in one or more of the monomer solutions used to create the membrane by an interfacial polymerization process. Incorporation of zeolite nanoparticles into the polymer matrix of seawater RO membranes has resulted in enhanced flux more than double that of a commercial product with 99.7% salt rejection. Incorporation of nanocomposite-based RO membranes has been reported to result in 20% lower energy consumption.

Nanotube membranes: The use of carbon nanotubes has also been shown to consume lower energy when compared to conventional seawater water RO desalination (Holt and Park, 2006; Sholl and Johnson, 2006; Truskett, 2003). Water and ions are transported through membranes

formed from carbon nanotubes that range in diameter from 6 to 11 Å. Membranes incorporating carbon nanotubes have been found to be promising candidates for water desalination using RO, as the size and uniformity of the tubes can achieve the desired salt rejection (Corry, 2008). A 10-fold permeability increase is expected using a carbon nanotube RO membrane, resulting in 30–50% energy savings. Simulations have shown that boron nitride nanotubes have superior water flow properties compared to carbon nanotubes and also achieve 100% salt rejection (Hilder et al., 2009). The use of a nanotube radius of 4.14 Å can functionalize the membrane to become cation-selective. When a nanotube radius of 5.52 Å is used, the membrane can be functionalized to become anion-selective (Hilder et al., 2009).

Biomimetic membranes: New developments have also occurred in the use of biomimetic membranes for desalination (Bowen, 2006). Biomimetic membranes are designed to mimic the highly selective transport of water across cell membranes. Natural proteins known as aquaporins are used to regulate the flow of water, providing increased permeability and high solute rejection. An illustration of aquaporins used in making desalination membranes is available at AquaZ Inc.'s Web site (AquaZ, 2011). Aquaporins act as water channels that selectively allow water molecules to pass through, whereas the transport of ions is restricted by an electrostatic tuning mechanism in the channel interior. The result leads to only water molecules being transported through the aquaporin channels and charged ions being rejected (Sui et al., 2001). Aquaporin membranes are considered to be 100 times more permeable than commercial RO membranes. Highly permeable and selective membranes based on the incorporation of the functional water channel protein Aquaporin Z into a novel triblock copolymer have been shown to have significantly higher water transport than existing RO membranes (Kumar et al., 2007). A particular difficulty to be overcome with biomimetic membranes is that they need to withstand high operating pressures, similarly to polymeric membranes.

The development of novel membrane materials with enhanced water passage and salt rejection can lead to the development of RO membranes with substantially lower feed pressure requirements and lower energy consumption. The nanocomposite membranes based on the incorporation of zeolite nanoparticles into the polyamide matrix have been tested at the pilot scale. Both nanocomposite and aquaporin membranes have been manufactured as spiral-wound elements. Commercial availability of nanocomposite membranes is expected by 2010. The development of nanotube membranes is still at the fundamental level and it will take several years before the product is viable for commercialization.

B.5.3.5 Application of Innovative Technologies

New technologies utilizing the principles of separation with membranes and electric fields have been introduced in recent years. These technologies have the potential to offer a substantial reduction in energy consumption for desalination. Some of these technologies are discussed below.

Forward osmosis: In the forward osmosis (FO) process, instead of using hydraulic pressure, as in conventional RO desalination processes, a concentrated draw solution is used to generate high osmotic pressure, which pulls the water across a semipermeable membrane from the feed solution (McCutcheon et al., 2005). The draw solutes are then separated from the diluted draw solution to recycle the solutes and to produce clean product water. A schematic of the FO process is shown in Figure B.12. A mixture of ammonia and carbon dioxide gas has been used as the predominant draw solution (McCutcheon et al., 2006). When ammonia and carbon dioxide are mixed in the right proportion, a solution with high osmotic pressure can be formed. This solution has been used for drawing water saline feeds. The advantage of using such a mixture for

a draw solution is that it has been shown to have the ability to be regenerated, when heated, and reused for the forward osmosis process. Thus, the FO process can be considered as a combination of membrane and thermal processes.

The energy utilized by the FO process has been reported to be approximately 25 – 45% of the thermal energy needed for multieffect distillation. FO has the added capability for using heat at a much lower or higher temperature than multieffect distillation processes. The FO process can use heat as low as 40 °C and as high as 200–250 °C. It has been reported that the electrical consumption of the FO process is substantially lower than that of existing desalination technologies. Specific energy consumption of less than 0.25 kWh/m^3 has been reported for the membrane part of FO (Cath et al., 2009). The process also has the advantage of lesser fouling propensity than for the reverse osmosis process. The lesser fouling and scaling propensity is attributed to the absence of hydraulic pressure and application of novel thin film composite membranes (Mi and Elimelech, 2010).

In an innovative approach to reducing energy consumption, FO has been used in combination with RO to form a hybrid process (Cath et al., 2009). A schematic of the hybrid process is shown in Figure B.13. In this novel approach, recycled water (tertiary treated effluent) is passed through a FO system, with seawater being used as the draw solution. The seawater is diluted by the recycled water within the FO process. The diluted seawater is then passed through a RO system where the feed pressure requirement is lowered by dilution of the seawater; hence lower energy consumption is obtained for the seawater desalination process. The concentrate (brine) from the RO process is further treated through a second stage FO process and the final seawater brine is discharged to the ocean. By using a combination of FO and RO, seawater desalination is performed with lower energy consumption and the recycled water is simultaneously treated through two physical barriers (FO and RO) (Cath et al., 2009).

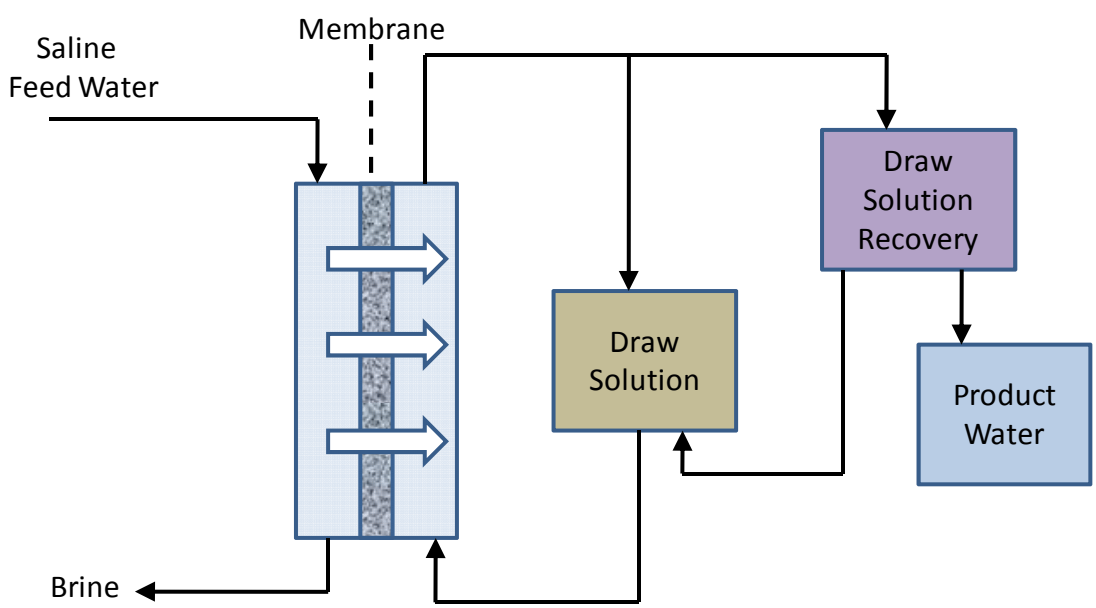

Figure B.12. Illustration of FO process.

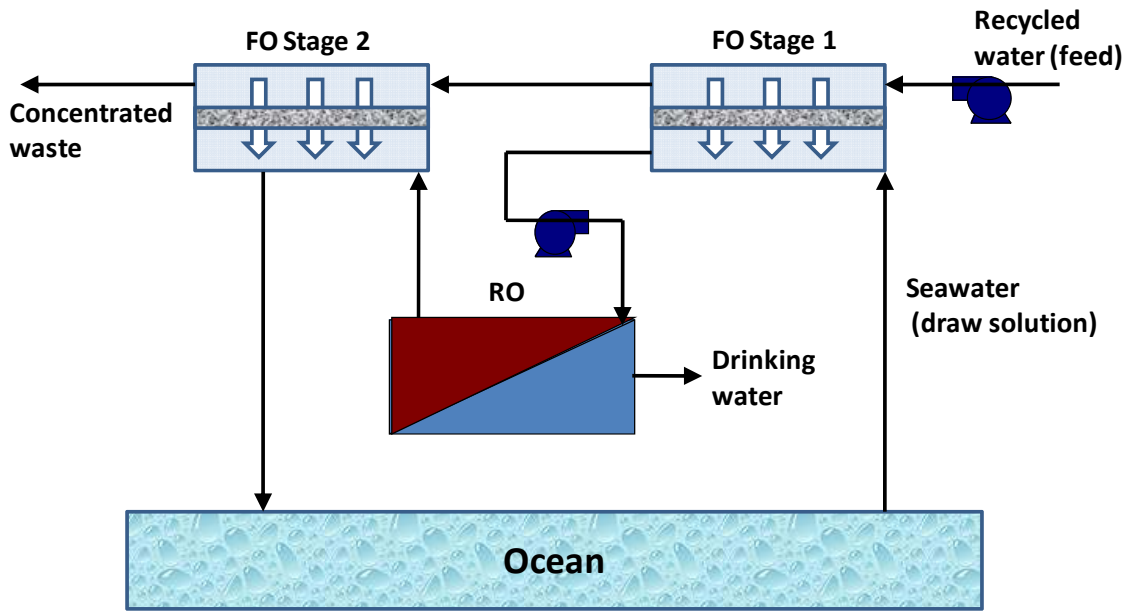

Figure B.13. Schematic of novel hybrid FO-RO process for water augmentation.

Ion concentration polarization: Ion concentration polarization has been utilized to desalinate seawater using an energy-efficient process (Kim et al., 2010). A schematic of ion concentration polarization is available from MIT (MIT, 2011). In this process, micro- and nanofluidics in combination with ion concentration polarization are used to desalinate seawater. Ion concentration polarization is a fundamental transport mechanism that occurs when an ionic current is passed through an ion-selective membrane. But, in the newly developed process, no membranes are utilized. An electrical potential is used to create a repulsion zone that acts a membrane separating charged ions, bacteria, viruses, and microbes from seawater flowing through a 500 × 100 μm microchannel. Water flows through the microchannel tangential to a nanochannel where the voltage is applied. The resulting force creates a repulsion zone and the stream splits into two smaller channels at a nanojunction. The two streams created are the treated water and concentrate. More than 99% salt rejection and 50% recovery have been reported using this process. The ion concentration polarization process has been reported to consume approximately 3.5 kWh/m^3 of energy (Kim et al., 2010). The process is best suited for small- to medium-scale systems, with the possibility of battery-powered operation.

Capacitive deionization: Although capacitive deionization (CDI) technology is not a recent discovery, several challenges exist for the identification of an optimum material for electrode manufacture (Farmar et al., 1997). The CDI technology was developed as a nonpolluting, energy-efficient, and cost-effective alternative to desalination technologies such as reverse osmosis and electrodialysis (Welgemoed, 2005). A schematic of CDI is shown in Figure B.14. In this technology, a saline solution flows through an unrestricted capacitor-type module consisting of numerous pairs of high-surface-area electrodes. The electrode material, typically carbon aerogel, has a high specific surface area (400–1100 m^2/g) and a very low electrical resistivity (less than 40 mΩ.cm). Anions and cations in solution are electrosorbed by the electric field upon polarization of each electrode pair by a DC power source. After the adsorption of ions, the saturated electrode undergoes regeneration by desorption of the adsorbed ions under

zero electrical potential or reverse electric field (Seo et al., 2010). Thus, the adsorption ability of the electrode is the key parameter for the performance of CDI technology.

When a potential is applied to CDI electrodes, counterions are attracted onto the electrode surface; simultaneously co-ions are expelled from the counterelectrode (Kim and Choi, 2010). This leads to a higher energy consumption and a lower operation efficiency because of the mobility of unwanted ions. Recently, modification of capacitive deionization has resulted in higher recovery and efficiency in a membrane–CDI (MCDI) technology (Kim and Choi, 2010; Biesheuvel and van der Wal, 2010). In the MCDI technology, ion-exchange membranes are used for selective transport of ions to the electrodes. This has resulted in higher efficiency and better energy consumption.

Energy consumption as low as 0.1 kWh/m^3 has been reported in using this technology for brackish water treatment (Welgemoed, 2005). For seawater desalination, energy consumption of 1.8 kWh/m^3 using a combination of ED and continuous electrodeionization (CEDI) was recently reported (Siemens, 2011). In the hybrid approach, an electric field is used to draw sodium and chloride ions across ion-exchange membranes. As the water itself does not pass through the membranes, the process can be operated at lower pressure and lower energy consumption. Seawater is pretreated with a self-cleaning disk filter, followed by UF modules. The ED–CEDI system consists of ED units arranged in series to remove high concentrations of salt, followed by CEDI units arranged in parallel to remove smaller amounts of salt. Besides energy savings, other advantages of the ED–CEDI technology include lower vibration and noise levels, improved safety, and minimal pre- and post-treatment (Siemens, 2011).

Voltea process: The Voltea process combines ED and CDI (Voltea, 2011). An illustration of the process is available from Voltea Inc. (Voltea, 2011). A three-step process is utilized, with the water flowing in a cell containing positively and negatively charged electrodes. The electrode surfaces are covered with ion-selective membranes, so ions in the feed water are attracted to the oppositely charged electrodes, pass through the membrane, and finally accumulate within the porous electrode structure. Up to 99% salt rejection has been reported using the process. When the electrodes become saturated, their polarity is reversed. The process is estimated to use less than 1.0 kWh/m^3 when removing 3,000 mg/L of salt from water. The system can operate at 90% recovery and can be equipped with an energy recovery system to reuse the energy stored in ions on the electrodes.

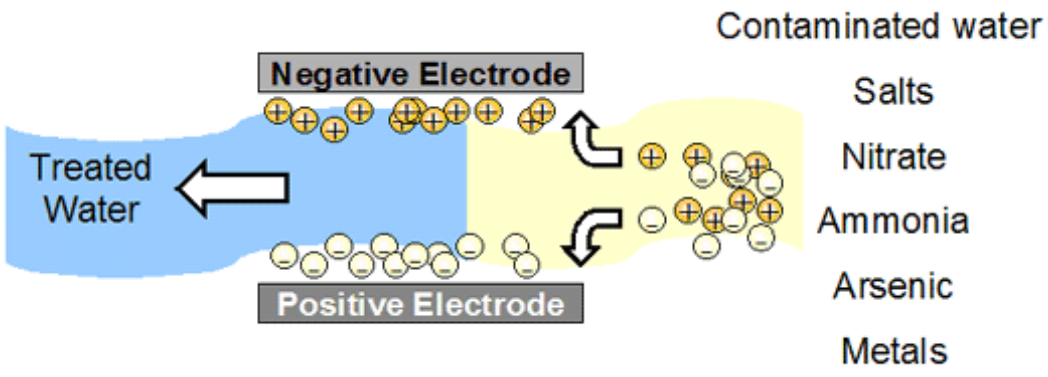

Figure B.14. Illustration of CDI process (NETL, 2011).

Table B.4. Specific Energy Consumption of CCD System While Desalinating Seawater with 35,000 mg/L of TDS (Desalitech, 2011)

Flux	kWh/m^3 at indicated recovery			
GFD	40%	45%	50%	55%
14.5	1.91	1.97	2.02	2.09
13.5	1.86	1.92	1.98	2.05
12.3	1.80	1.86	1.91	1.99
11.1	1.75	1.80	1.86	1.93
9.8	1.70	1.75	1.80	1.88
8.6	1.65	1.70	1.75	1.82

Saltworks process: The Saltworks process involves a thermo-ionic system that can operate on waters with feed water TDS range of 20,000 to 80,000 mg/L (Saltworks, 2011). A schematic of the thermo-ionic system is available from Saltworks Inc. (Saltworks, 2011). The thermo-ionic process uses ion-exchange membranes in an arrangement resembling an EDR system. However, in the thermo-ionic system, energy contained within a concentrated salt solution, rather than external power, is used for the desalination process. The hypersaline solution is produced in a special evaporative unit that operates at a temperature 10 °C warmer than the ambient wet bulb temperature (Saltworks, 2011). The system utilizes a proprietary ion-exchange membrane. Besides solar heat or other low-grade heat sources for the evaporative unit, the only external energy requirement is the electricity needed to operate the circulation pumps and fans. The remaining energy for the desalination process is produced by the hypersaline solution. A commercial unit for operation and testing is expected in 2012 (Saltworks, 2011).

Closed-circuit desalination: Closed-circuit desalination (CCD) is another proprietary technology based on a hydrostatic process at the core of the water treatment system that reduces desalination costs by more than 20% (Desalitech, 2011). The CCD process lowers the feed pressure required for desalination and hence reduces energy consumption. Its performance is being proven in several currently operating commercial installations using the same membranes and pumps as in conventional RO, but configured in a new way. The CCD process recycles concentrate until a desired recovery level is achieved, replacing brine with fresh feed without disrupting continuous permeate production and with practically no energy loss. The process has the advantage of 30–40% reduced energy consumption, reduction of equipment costs, and maximum feed water recovery (Desalitech, 2011). Energy consumption of the CCD process at various recoveries and flux is shown in Table B.4. Compared to a RO system with the same number of elements, a permeate flux of 8 GFD, and a recovery rate of 45% while consuming over 2.5 kWh/m^3, the CCD system has an energy consumption of 1.7 kWh/m^3.

B.5.4 Energy Minimization for Advanced Water Treatment Processes

When RO is used for AWT and reuse, the same strategy for energy minimization as described in the previous section can be used. When low-pressure membranes are used for pretreatment, the energy efficiency is determined largely by the membrane permeability and the backwashing frequency (Chang et al., 2008). More frequent backwashing decreases the energy efficiency of the membrane system. Backwashing frequency and duration are optimized through careful selection of pretreatment practices and proper membrane selection (Crozes et al., 2003; Jacangelo et al., 1992).

When MBR systems are used, the submerged configuration reduces energy consumption as well as vacuum pressure (Chang et al., 2008). When a MBR system was operated with vacuum at negative 1 to negative 10 psi, the energy consumption was estimated to be 327,000 kWh per year (NYSERDA, 2004). In another study (Zhang et al., 2003), a transverse flow of water was used instead of a cross-flow mode to enhance filtration capacity and reduce fouling. A two-loop connection between the bioreactor and the membrane module was used to allow for low recirculating flow between the membrane and bioreactor. Additionally, the design required no cooling device. The investigators found that the membrane module consumed the majority of the energy.

For ozonation systems, understanding the electricity rate structure, installing energy monitoring devices, analyzing loads and energy consumption, and assessing process modifications can optimize energy consumption (Chang et al., 2008). Energy optimization opportunities can be classified into three categories (DeMers et al., 1996): Type 1—operations and maintenance activities; Type 2—operation and maintenance evaluation prior to implementing process changes; and Type 3—design change or system modifications. Examples of Type 1 include calibrating gas flow meters, ozone residual monitors, and power meters; inspecting and cleaning ozone generator dielectrics; and adjusting ozone dosage to match diurnal changes in ozone demand. Examples of Type 2 include extending a desiccant dryer cycle, decreasing system operating pressure, and utilizing an existing refrigerant dryer bypass. Examples of Type 3 include installing smaller compressors, bypassing/modifying a refrigerant dryer or chiller, modifying ozone residual sampling, and monitoring to accurately detect residual inside contactor.

Although UV is considered post-treatment, a dose control strategy is considered to be the most effective way to reduce energy consumption (Chang et al., 2008). This type of strategy alters the number of lamps in use or the lamp power based on the flow rate, level of disinfection required (dose), and water quality (such as UV transmittance) (USEPA, 2003). Settings on the transformer can be made to allow the lamps to be dimmed to 60% of the high-intensity setting to adjust for low flow or good influent water quality (EPRI, 1994). Low-pressure–low-intensity lamps operate optimally at 40 °C and a variation from this temperature can reduce lamp intensity by 1-3% per degree (NYSERDA, 2004). Lamp energy efficiency will also be affected by fouling of the lamp housing. Fouling reduces the amount of UV light, requiring that the lamps be operated at a higher intensity to maintain the same dose (Chang et al., 2008). Fouling is a function of the influent water quality, lamp configuration, and system hydraulic characteristics (Job et al., 1995; Mackey et al., 2001; NYSERDA, 2004). Hydraulic conditions and UV lamp configuration can also affect energy efficiency. Different possible UV lamp configurations are shown in Figure B.15. A linear configuration is considered to be the most energy-efficient for UV lamps to avoid UV emission losses due to self-absorption, reflection, or refraction (NYSERDA, 2004).

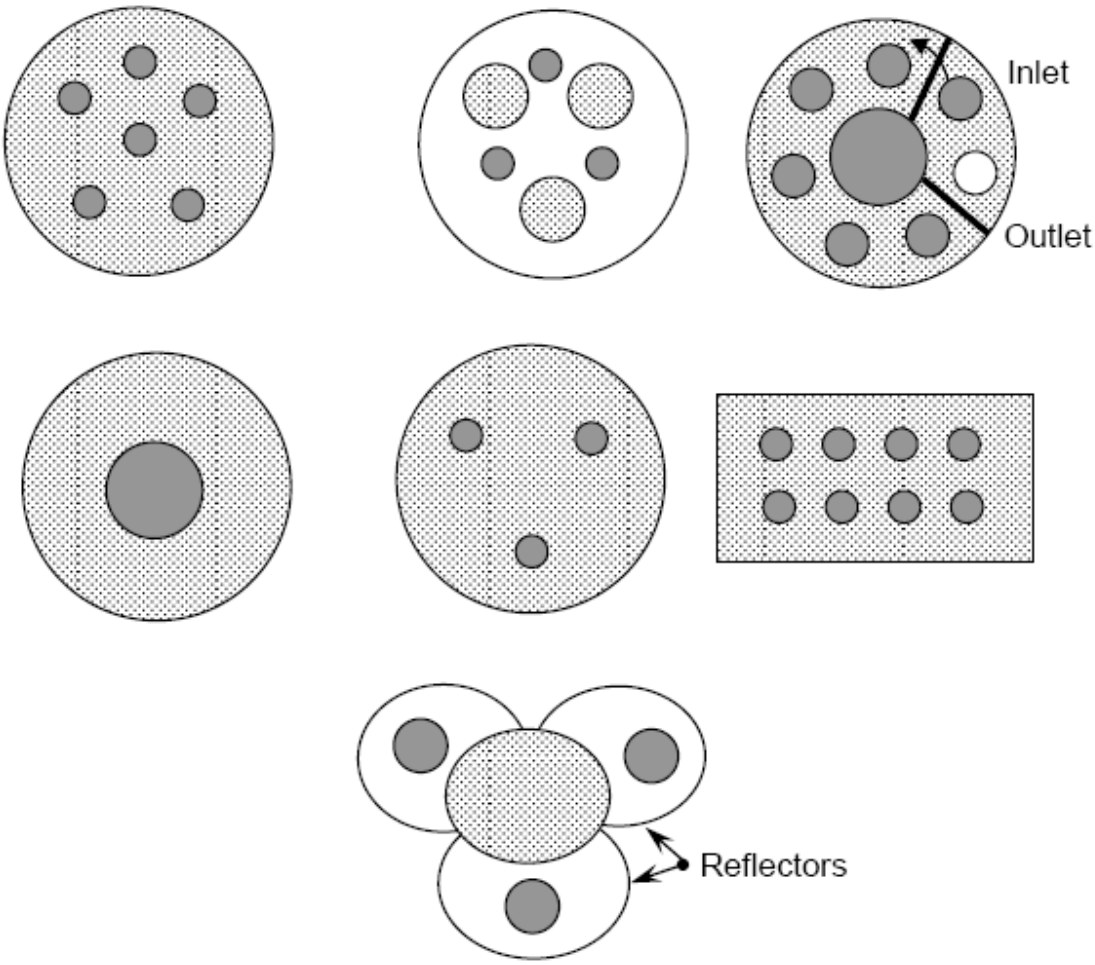

Figure B.15. Possible lamp configuration in flow-through UV disinfection systems (NYSERDA, 2004). *Note:* The solid gray circles represent the UV lamps. Dotted circles represent the water-filled areas.

APPENDIX C:
Evaluation and Optimization of Emerging and Existing Energy Recovery Devices for Desalination and Wastewater Membrane Treatment Plants

Evaluation and Optimization of Emerging and Existing Energy Recovery Devices for Desalination and Wastewater Membrane Treatment Plants

About the WateReuse Research Foundation

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

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

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Evaluation and Optimization of Emerging and Existing Energy Recovery Devices for Desalination and Wastewater Membrane Treatment Plants

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Acronyms

AACE	Association for the Advancement of Cost Engineering
APM	axial piston motor
APP	axial piston pump
AValue	membrane water permeability coefficient
AvgConc	average concentration of the ion
BCorrectionByIon	correction factor for the ion
BCS	brine conversion systems
BetaCoef	concentration polarization coefficient
BP	booster pump
BSU	Bonita Springs Utilities
BValue	membrane salt (ion) permeability coefficient
BW	brackish water
BWRO	brackish water reverse osmosis
CFU	colony forming units
CIP	clean in place
CP	concentration polarization
CRBS	Colorado River Basin States
DWEER	Dual Work Exchange Energy Recovery (Flowserve/Calder)
ERD	energy recovery device
ERI	Energy Recovery Inc.
FEDCO	Fluid Equipment Development Company
FS-ERD	Fluid Switcher Energy Recovery Device
gfd	gallons per square foot per day
gpd	gallons per day
gpm	gallon per minute
HALO	High Pressure Turbocharger (ERI)
HEMI	Hydraulic Energy Management Integration
HER	Hydraulic Energy Recovery
HP	high pressure
HPB	Hydraulic Pressure Booster (FEDCO)
HPP	high-pressure pump
HPP eff	high-pressure RO feed pump efficiency
HSD	homogenous solution diffusion
HTC	Hydraulic Turbocharger (ERI)
IDA	International Desalination Association
IPER	integrated pumping and energy recovery

kWh/kgal	kilowatt-hour per kilogallon
kWh/m^3	kilowatt-hour per cubic meter; a unit of energy consumption
LinX	Linear Exchanger
lmh	liter per square meter per hour
LP	low pressure
LPAWTP	Luggage Point Advanced Water Treatment Plant
LP-HEMI	low-pressure hydraulic energy management integration
LPWWTP	Luggage Point Wastewater Treatment Plant
LPT	Low Pressure Turbocharger (ERI)
L/s	liter per second
µmho/cm	micromhos per centimeter
MF	microfiltration
MG	million gallons
mgd	million gallons per day
mg/L	milligram per liter; a unit of concentration
MIX	volumetric mixing constant for the ERD
MLD	million liters per day
mri	membrane replacement interval
MWh/yr	megawatt-hour per year
NF	nanofiltration
ng/L	nanogram per liter
NPV	net present value
nte	net transfer efficiency (for an ERD)
NTU	nephelometric turbidity unit
OSHA	Occupational Safety and Health Administration
Pbr	brine pressure at ERD inlet
Pe	brine pressure at ERD exit
PEI	Pump Engineering, Inc. (ERI)
PermConc	permeate concentration of ion
PES	Pressure Exchange System
PFD	process flow diagram
PIT	Pelton impulse turbine
Pnet	net driving pressure
PSDP	Perth Seawater Desalination Plant
psig	pounds per square inch gauge; a unit of pressure
PWER kW	energy recovered by the Pelton wheel
PWMRi	present worth of the membrane replacements over the equipment life
PX	Pressure Exchanger (ERI)
REC	product recovery rate
RO	reverse osmosis
Rr	ratio of the RO brine (concentrate) flow to the RO feed flow

RR	reject ratio
RWE	Rotary Work Exchanger
SCADA	supervisory control and data acquisition
SDI	Silt Density Index
SEC	specific energy consumption
SW	seawater
SWRO	seawater reverse osmosis
TBSDF	Tampa Bay Seawater Desalination Facility
TDS	total dissolved solids
TFSP	Total Flux and Scaling Program
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
USEPA	U.S. Environmental Protection Agency
UV/AOP	ultraviolet disinfection/advanced oxidation
VFD	variable frequency drive
WRF	WateReuse Research Foundation

Foreword

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

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

- Defining and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

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

In WRF-08-14, a literature review and manufacturer assessment was conducted on energy recovery devices and their use in the desalination of brackish water, seawater, and wastewater. Based on typical municipal requirements, an integrated mass-balance, reverse-osmosis projection software, energy recovery, and cost estimating model was developed. The Excel-based tool permits utilities, engineers, and plant operating staff to provide greenfield, cost-based decisions on which, if any, commercially available energy recovery device to implement in their desalination facilities.

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El Paso Utilities District, TX
Energy Recovery, Inc.
Florida Keys Aqueduct Authority
Hydranautics
Irvine Ranch Water District, CA
Long Beach Water Department, CA
Sweetwater Authority, CA
Tampa Bay Water, FL
Toray Membranes USA
West Basin Municipal Water District, CA

Executive Summary

Water withdrawals from oceans, rivers, lakes, and ground in the United States exceeded 410 billion gallons per day in 2005 (Kenny et al., 2005). More than 201 billion gallons per day (gpd; approximately 48% of the total) are withdrawn to support power generation. Based on 2005 census data, the per capita withdrawal of water resources in the United States exceeded 1420 gpd (U.S. Census Bureau, 2005). In regions with low precipitation and seawater intrusion of coastal aquifers, coupled with population growth, it is anticipated that existing water resources will become increasingly stressed. The U.S. Bureau of Reclamation reported nearly 30 years ago that Lower Colorado River Basin water use exceeded the renewable water resources of the region (U.S. Geological Survey, 1984). As a result of these demands, water resource planners are turning to desalination of impaired waters such as saline groundwater, treated wastewater, estuarial surface water, and seawater to provide an alternative water supply for communities and industries. A recent study commissioned by the Colorado River Basin States (CRBS) identified 12 different augmentation options for water resources in the Lower Colorado River Basin. Of these, three options focused on the desalination of brackish water, seawater, and treated wastewater (CRBS, 2008).

Reverse osmosis (RO) is widely used to desalt brackish water and seawater for drinking and industrial water production and to reclaim wastewater effluent for indirect potable reuse and industrial use. There are many seawater reverse osmosis (SWRO) plants in the Middle East, where this is a predominant water source. Within the last five years, every major city in Australia has constructed a SWRO desalination plant to supplement the drinking water supply. As the total dissolved solids (TDS) of seawater are typically around 35,000 milligrams per liter (mg/L), this water will have a substantial osmotic pressure, and thus feed pressures of around 800 to 1000 psig are typically required. A major impediment to additional implementation of desalination technologies is the lack of an independent tool to evaluate energy consumption and minimization of energy use.

ES.1. Energy Consumption in Reverse Osmosis Systems

Early seawater desalination plants operated without energy recovery, with energy consumption greater than 10 kilowatt-hours per cubic meter (kWh/m^3) (Dundorf et al., 2007). The high energy consumption limited the application of RO for seawater desalination to locations where freshwater supplies were either absent or very limited. Over time, through steady improvements in the permeability (water mass transfer) of RO membranes, in combination with the development of improved energy recovery devices (ERDs), the energy consumption of SWRO systems has been reduced significantly. As shown in Figure ES-1, significant reductions in energy consumption have been achieved , with demonstration of energy consumption as low as 1.6 kWh/m^3 through the use of a conservative system design composed of high-permeability RO membranes, a positive displacement high-pressure pumps, and positive displacement work exchanger ERDs (Dundorf et al., 2007). For full-scale plants, energy consumption between 2.0 and 2.4 kWh/m^3 is typical, with full-plant energy consumption, including raw water pumping, pretreatment, chemical dosing, post-treatment, and residuals disposal, typically in the range of 3.0 to 3.5 kWh/m^3.

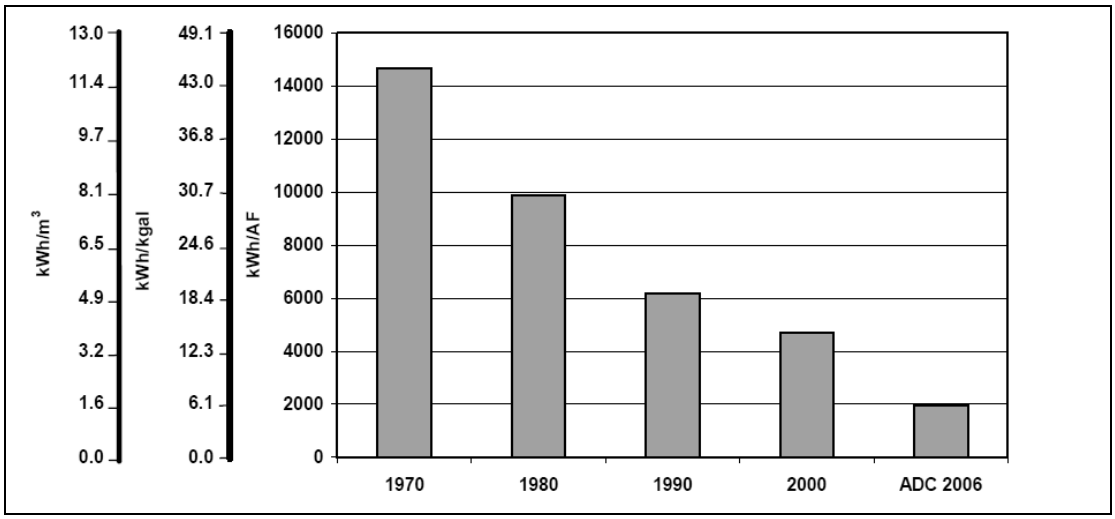

Figure ES.1. History of power consumption required for seawater desalination process equipment (Dundorf et al., 2007).

ES.2. Use of Energy Recovery Devices in Desalination

ERDs utilized in RO applications convert residual hydraulic energy into mechanical energy that is reapplied either to the RO feed (for seawater applications) or to an interstage feed (for brackish or wastewater applications) in order to reduce the energy input to the RO system. Two general classifications of ERDs are commercially available and are utilized in the desalination industry: centrifugal devices and isobaric devices. Table ES.1 outlines commercial ERDs that are available on the market.

Centrifugal devices can further be classified into direct-coupled devices and turbocharger devices. Direct-coupled devices, including the Pelton Wheel and Francis Turbine, are direct-coupled to a high-pressure pump (HPP) and motor shaft. Rotational energy imparted to the turbine from converted concentrate pressure is transferred directly to the motor shaft, reducing the motor power requirements. The HPPs for a direct-coupled device are sized for the full feed flow and pressure; however, the motor power can be reduced as a result of energy recovery.

In a turbocharger device, a turbine is direct-coupled to a pump impeller on a common shaft and located downstream from the HPP. Rotational energy imparted to the turbine from converted concentrate pressure is reconverted to pressure energy through the impeller and used to boost either the RO feed pressure (for seawater systems) or interstage pressure (for brackish or wastewater systems). The HPP is sized for the full feed flow, but the head requirement is decreased by the boost pressure provided through the turbocharger.

For isobaric devices, a side stream of the low-pressure feed and the concentrate stream are directed to a positive displacement device. Energy from the concentrate stream is imparted directly into the feed stream. A small booster pump is typically needed to raise the pressure of the side stream to the feed pressure. The HPP is sized for the permeate flow of the RO system and the full feed pressure. Isobaric devices typically have the highest efficiency of the ERDs, but require additional equipment and may allow leakage between the concentrate and feed/interstage streams.

Table ES.1. Commercially Available Energy Recovery Devices

Manufacturer	Device Type	Trade Name	Capacity Range (m^3/d) per Device*
Flowserve/Calder	Centrifugal	Pelton Wheel	360 to 24,000
PEI (division of ERI)	Centrifugal	Turbocharger	136 to 65,500
FEDCO	Centrifugal	Turbocharger	360 to 84,000
Danfoss	Isobaric	iSAVE	504 to 960
Energy Recovery Inc.	Isobaric	PX	109 to 1640
Flowserve/Calder	Isobaric	DWEER	2400 to 8,450
Aqualyng	Isobaric	Recuperator	Proprietary
Spectra Watermakers	Isobaric	Clark Pump	<10
Spectra Watermakers	Isobaric	Pearson Pump	24 to 40
KSB	Isobaric	SalTec	Up to 20,000

*Note that most ERDs are easily operated in parallel for larger capacities.

ES.3. Development of a Decision-Making Tool for Implementation of ERDs at Municipal Desalination Plants

As part of WRF-08-14, CH2M HILL developed a computer-based tool to evaluate current and emerging ERDs based on their performance, applicability, and life-cycle costs. The model covers all known and applicable commercially available ERDs and all associated systems that impact energy recovery.

The tool allows the user to develop an optimum RO system design (such as number of stages, recovery and flux, and flow and pressure of various streams) based on feed water quality and desired product water quality. The membrane type (low-pressure or high-rejection), number of passes, percentage of bypass, and ERD are examples of the options available to the user to customize the model run to a project. The tool is based upon common process configurations utilized in desalination plants.

The tool output will show the energy consumption when no ERD is used, display comparative performance (based on energy consumption, operating costs, and life-cycle costs) of these devices, and indicate the overall energy consumption, operating costs, and capital costs associated with the system. Figure ES.2 illustrates a screen capture of the tool's operator interface.

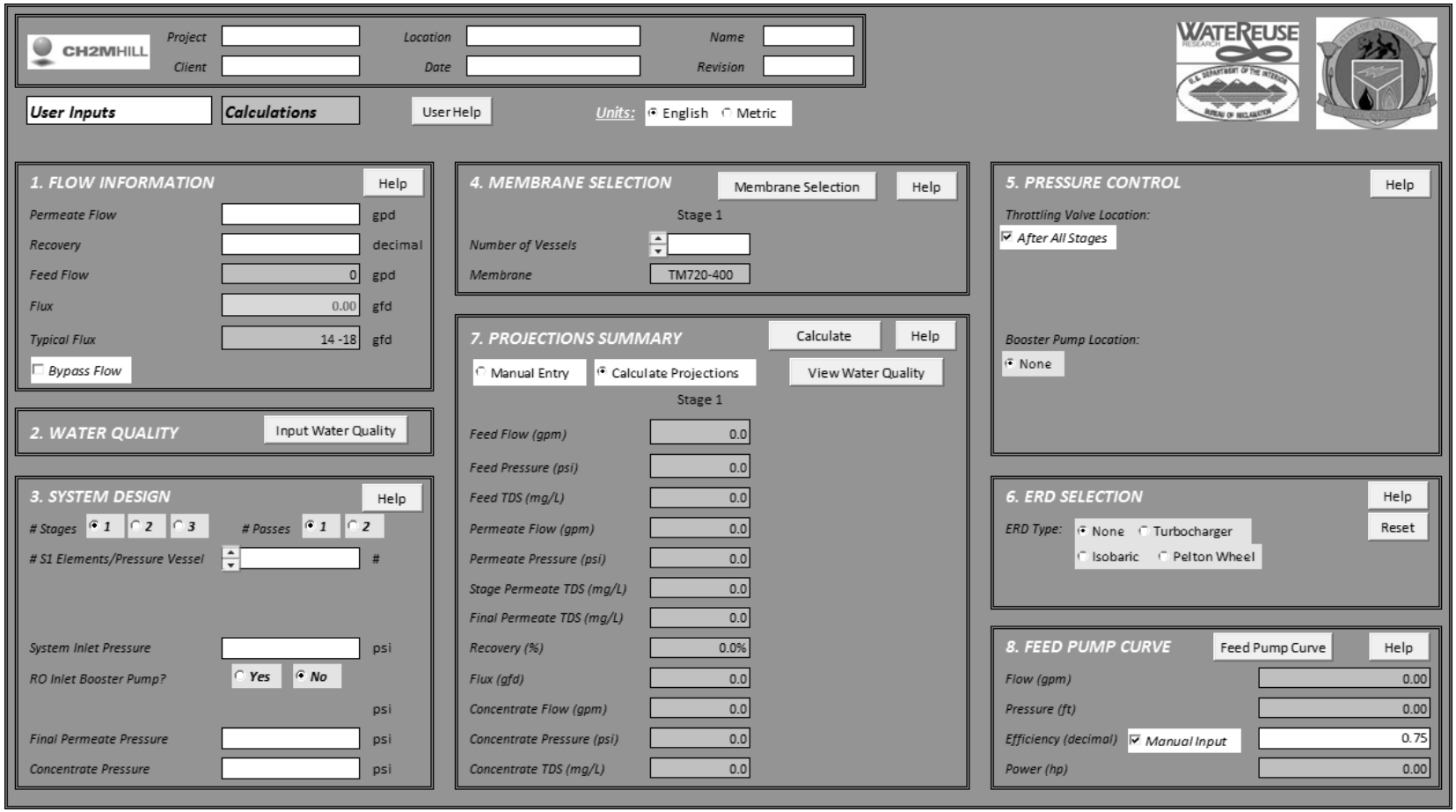

Figure ES.2. Screen shot of the operator interface for the ERD tool.

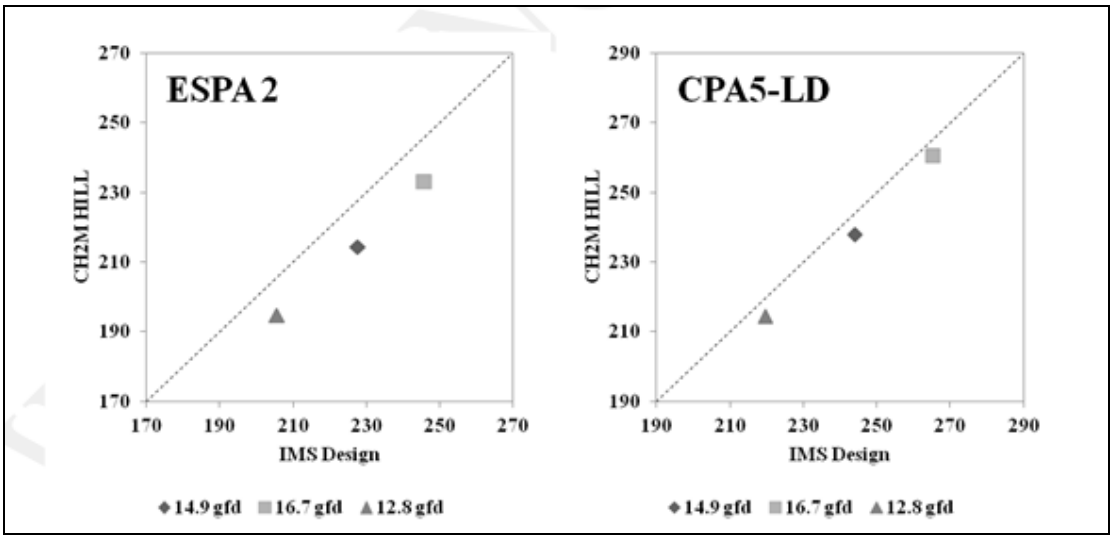

Figure ES.3. WRF-08-14, CH2M HILL developed tool vs. RO manufacturer's projection software, feed pressure (psi).

The tool utilizes a RO projection calculation algorithm similar to that developed by Thomas Wolfe of Perlorica under contract to the U.S. Environmental Protection Agency (USEPA), called the Total Flux and Scaling Program (TFSP). Figure ES.3 shows that the model provides a reasonable representation of the manufacturers' projection software.

Five different case studies were compared to the tool:

- Case Study #1: Eastern Municipal Water District, Perris I BWRO facility
    - This is a brackish groundwater desalter using a turbocharger ERD. The tool's prediction of feed and ERD boost pressure are within 5% of the actual April 2012 operational numbers.
- Case Study #2: Bonita Springs Utilities, BWRO facility
    - Bonita Springs is a brackish water desalter that has been in operation since 2004 and is experiencing increasing feed salinity. This plant was recently retrofitted with a turbocharger-type ERD. The tool confirms the engineer's estimate that the turbocharger is the best choice for the retrofit despite the fact that the isobaric ERDs have a substantially higher efficiency.
- Case Study #3: Luggage Point Advanced Water Treatment Plant, water reuse RO
    - Luggage Point incorporates a three-stage RO system operating on microfiltered effluent. The tool demonstrates the advantage of placing a turbocharger between Stages 2 and 3 versus Stages 1 and 2. The comparison between the actual operating data and the tool indicate that the predicted membrane feed pressure and turbocharger boost pressures are accurate within 5 and 7%, respectively.
- Case Study #4: Tampa Bay Water, desalination plant
    - Tampa Bay incorporates a two-pass RO system operating on ocean water. A Pelton wheel ERD is utilized. Energy consumption data for a single RO train was obtained from the operating staff and compared with the estimate provided by the tool. The tool was within 4% of the kilowatt (kW) value reported.

- Case Study #5: Perth Seawater Desalination Plant, Kwinana Beach, Australia
    - Perth is a two-pass RO system operating on ocean water. The system included ERI PX type isobaric ERDs and the tool confirms that the isobaric-type ERD is the best choice.

For available data, the tool provides a reasonable estimate of the capital and operating costs associated with the ERD selected.

ES.4. Conclusions

To fill a need in the desalination community, an Excel-based computer tool was developed with the following functionality:

- RO mass balance
- RO projections
- Incorporation of ERDs
- Calculation of power consumption
- Estimation of capital costs
- Estimation of electrical operating costs

The tool provides a valuable new resource for municipal planners, operators, and consulting engineers in evaluating energy recovery options in desalination of brackish water, treated wastewater, and seawater using RO technology.

Chapter 1

Introduction

Water quenches our thirst, cools our industries, and irrigates our fields. Upon it, approximately 95% of the international imports and exports of the United States are transported. Beneath it lies a substantial source of food. Without it, we cannot survive. As Jacques Cousteau once stated, "the cycle of life is intricately tied up with the cycle of water."

Water withdrawals from oceans, rivers, lakes, and ground in the United States exceeded 410 billion gallons per day in 2005 (Kenny et al., 2005). More than 201 billion gpd (approximately 48% of the total) are withdrawn to support power generation. Based on 2005 census data, the total withdrawal of water resources per capita in the United States exceeded 1,420 gpd (U.S. Census Bureau, 2005). In regions with low precipitation and seawater intrusion of coastal aquifers, coupled with population growth, it is anticipated that existing water resources will become increasingly stressed. The U.S. Bureau of Reclamation reported nearly 30 years ago that Lower Colorado River Basin water use exceeded the renewable water resources of the region (U.S. Geological Survey, 1984).

Increasingly, water resource planners are turning to desalination of impaired waters such as saline groundwater, treated wastewater, estuarial surface water, and seawater to provide an alternative water supply for communities and industries. A recent study commissioned by the Colorado River Basin States (CRBS) identified 12 different augmentation options for water resources in the Lower Colorado River Basin. Of these, three options focused on the desalination of brackish water, seawater, and treated wastewater (Colorado River Basin States [CRBS], 2008).

Although desalinated seawater has been identified as a viable alternative water source, advocacy opposition groups have been organizing to limit the implementation of desalination, with a specific emphasis on the high energy consumption of seawater desalination. One group states that "More energy is required to produce water from desalination than from any other water-supply or demand-management option in California" (Cooley et al., 2006). Another advocacy agency indicates that "Unless existing technology becomes significantly more energy efficient, the total expense of desalination is not likely to decrease. In fact, with oil prices rising around the globe, it is possible that the technology will remain prohibitively expensive even if the equipment substantially improves" (Food and Water Watch, 2009). Although the analyses conducted by these opposition advocacy agencies are suspect, it is evident that the energy consumption of desalination continues to be a focus of those opposed to desalination. As a result, continued effort to minimize energy consumption by desalination plants and ensure that the industry is using accurate energy and cost reporting is important to ensure that desalination is recognized by the public as a viable water augmentation source.

1.1 Energy Losses in Reverse Osmosis Systems

Desalination in the United States and in many other parts of the world is typically performed using a process called reverse osmosis (RO). In the RO process, water is pumped tangentially along the surface of a semipermeable membrane in a cross-flow configuration. A portion of the water passes through the membrane to become high-quality permeate, whereas the

remaining portion of the water, containing nearly all of the solutes, becomes the concentrate stream. A simplified process schematic for the RO process is shown in Figure 1.1.

A schematic of a spiral-wound membrane is shown in Figure 1.2. The element is formed from a number of membrane "leaves" connected to a central permeate tube. Each leaf consists of two sheets of membrane, with a permeate spacer between them. The membrane sheets are glued on three sides, with the final edge bonded to the permeate tube. A feed spacer is placed between each pair of leaves before all leaves are rolled around the tube. Once they are rolled, the anti-telescoping devices and a fiberglass wrap are added to complete the element.

In RO systems, elements are housed in pressure vessels, with each vessel containing as many as eight elements connected in series via product water interconnectors. Up to 15% of the feed water processed by an individual element is converted to permeate, or recovered. Thus, by arranging elements in series, up to 65% permeate recovery can be obtained within a single pressure vessel. To achieve the desired permeate capacity, pressure vessels are arranged in parallel to increase the capacity of the system; the parallel vessels are referred to as a stage or bank. To increase recovery further, banks of pressure vessels can be placed in series (staging), with up to three stages used to achieve recoveries as high as 90%. Typical recoveries for RO systems treating brackish water and secondary effluent are 70 to 90% using two and three stages. Recoveries for systems treating seawater range from 35 to 60% depending on seawater salinity and temperature. Seawater RO (SWRO) recoveries are lower because of high osmotic pressure coupled with a maximum operating pressure range for the RO elements (typically 1000 pounds per square inch gauge [psig]).

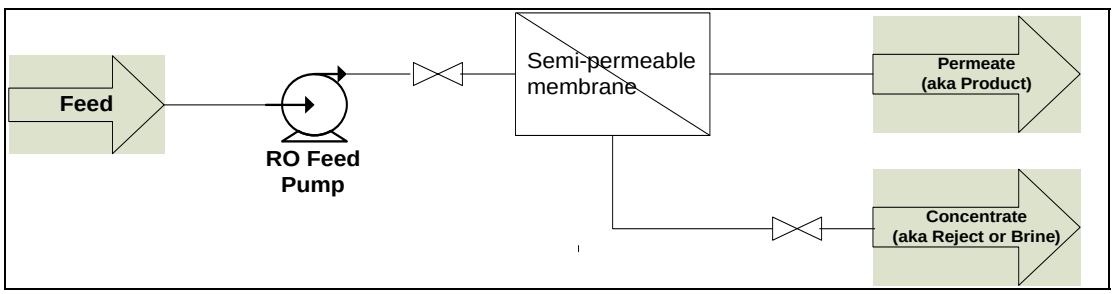

Figure 1.1. Simplified reverse osmosis flow diagram.

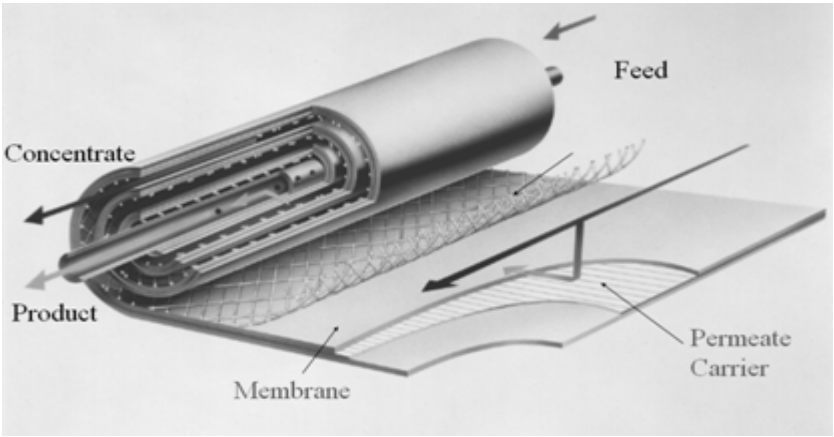

Figure 1.2. Schematic of a reverse osmosis membrane (Bartels et al., 2007).

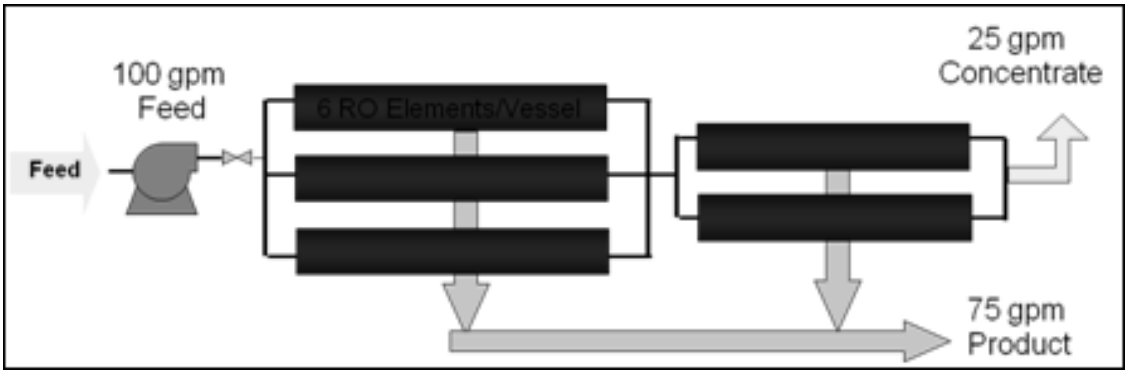

Figure 1.3. Sample two-stage RO system operating at 75% recovery.

Figure 1.3 displays a sample two-stage RO system operating at 75% recovery.

In general, the RO process can remove more than 99% of all dissolved minerals and more than 95% of organic compounds from water, as well as biological and colloidal suspended matter, including turbidity. Removal levels can be lower for specific solutes, depending on their characteristics (e.g., molecular size, charge, charge density). Given these removal levels, RO is a broad-spectrum removal technology and, as such, is widely utilized for treatment of a variety of impaired waters in both municipal and industrial applications and is the preferred desalination process.

RO is widely used to desalt brackish water and seawater for drinking and industrial water production and to reclaim wastewater effluent for indirect potable reuse and industrial use. There are many SWRO plants in coastal and island communities and the Middle East, where they are a predominant water source. Within the last five years, every major city in Australia has constructed a SWRO desalination plant to supplement its drinking water supply. As the TDS of seawater are typically around 35,000 milligrams per liter (mg/L), this water will have a substantial osmotic pressure, and thus feed pressures of around 800 to 1000 psig are typically required.

There are numerous applications where RO is used to reduce the total organic carbon (TOC) and total nitrogen of microfiltered municipal wastewater. Such applications produce water suitable for industrial processes, such as boiler feed water. Municipal wastewater RO applications usually involve rapid and irreversible fouling of the membrane surface over the first few weeks of operation. This fouling results in an increase in required feed pressure to maintain the system capacity. Thus, although the TDS of treated wastewater, and therefore its osmotic pressure, are low in comparison to seawater, reuse RO systems can still experience feed pressures of up to 300 psig.

Energy consumption in RO processes is influenced by a number of factors, including the osmotic pressure of the feed water, the water mass transfer characteristics of the membrane, system recovery, and the pressure drop across the element (from feed to concentrate).

Osmotic pressure is discussed in more detail in Chapter 3. The feed pressure to the RO membranes must overcome the osmotic pressure before a single drop of permeate will be produced. The osmotic pressure for a salt solution can be estimated as 1 pound per square inch (psi) per 100 mg/L TDS for fresh and brackish waters. As the feed water passes through the RO system, salinity on the feed side of the membrane increases as salts are concentrated

in a decreasing volume of water. Thus, as recovery increases, solute concentrate in the feed-concentrate stream increases and osmotic pressure increases. The effect of the osmotic pressure as a function of element position in the example RO system is shown in Figure 1.4; assuming that the feed TDS is 1500 mg/L and all of the solutes are rejected by the RO membrane, the concentrate TDS will be 6000 mg/L, resulting in a concentrate osmotic pressure of 60 psi. (Brackish water RO membranes allow 0.5 to 1.0% of solutes to pass into the permeate, so concentrate TDS will be slightly less than 6000 mg/L.) To provide an equivalent "net driving pressure" over a two-stage system operating at 75% recovery compared to one operating at 50% recovery (to maintain equivalent permeate flow), a higher feed pressure is needed to counteract the increase in osmotic pressure.

There is a loss of pressure, typically 2 to 3 psi, as water passes through the feed spacer from the feed end of the element to the concentrate end, with actual loss a function of flow rate, spacer thickness, and geometry. As elements are placed in series, this feed-concentrate pressure loss or "drop" can become significant. Furthermore, as more membranes are placed in series in the RO system, the hydraulic resistance associated with differential pressure increases. This differential pressure exists both on the feed-concentrate spacers of the membrane and in the permeate spacer of the membrane. RO membrane differential pressure is a function of flow rate and membrane feed spacer thickness, but is estimated at approximately 3 psi per membrane for new membranes. With 12 membranes in series, per the previous example, this equates to about 35 psi. Therefore, we would require 95 psi to produce any water at the tail end of the system. Note that if the feed salinity to the system was 15,000 mg/L, the concentrate salinity would be approximately 60,000 mg/L and the concentrate would have an osmotic pressure of approximately 640 psi. This is why high-salinity water such as seawater requires such high feed pressures.

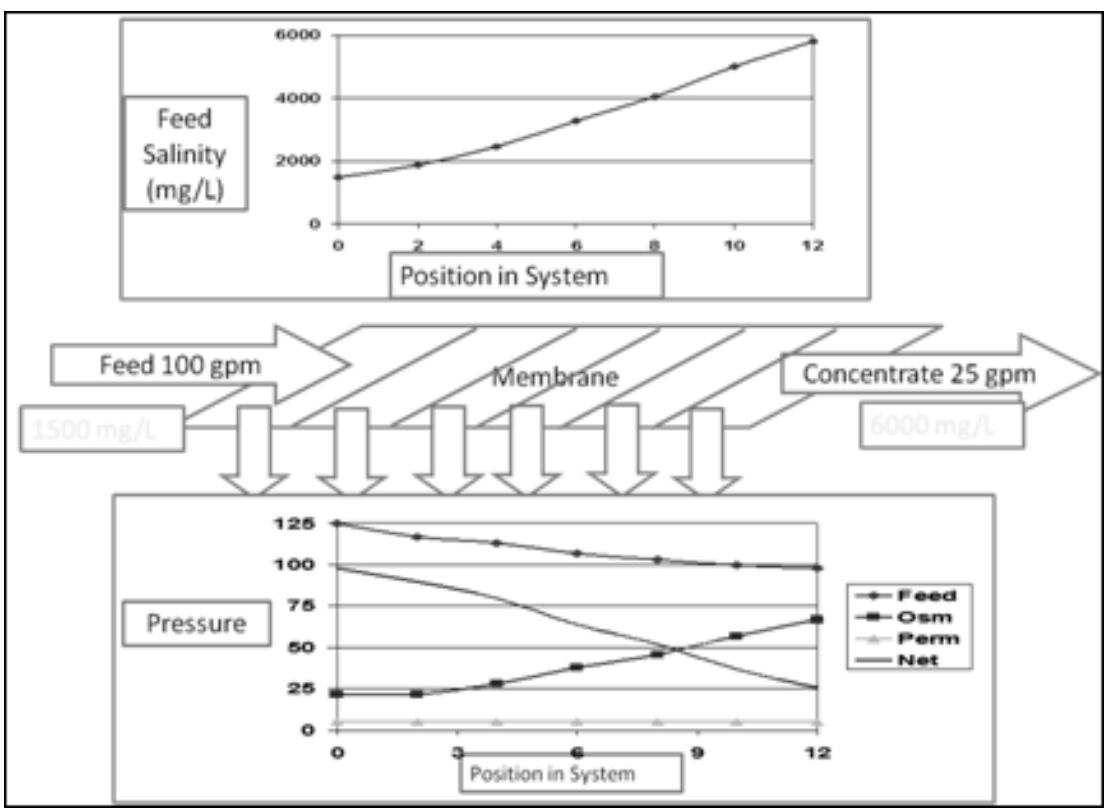

Figure 1.4. Effect of the osmotic pressure as a function of element position.

RO membrane technology has improved dramatically over the years. Currently, the mass transfer characteristics are so good that the membrane material resistance is minimal and the RO systems are operating near what is termed the "thermodynamic restriction," where the resistance that generates the required net driving pressure is essentially the osmotic pressure and hydraulic pressure differential only (Zhu et al., 2010).

1.2 Energy Consumption in Reverse Osmosis Systems

The desalination industry, through free market principles, has long recognized the impacts of energy consumption in desalination. Early seawater desalination plants operated without energy recovery, with energy consumption greater than 10 kilowatt-hours per cubic meter (kWh/m^3). This high energy consumption limited the application of RO for seawater desalination to locations where freshwater supplies were either absent or very limited. Over time, through steady improvements in the permeability (water mass transfer) of the RO membrane, in combination with the commercial development of energy recovery devices (ERDs), energy consumption of SWRO systems has been reduced significantly. As shown in Figure 1.5, testing performed by the Affordable Desalination Collaboration in 2007 demonstrated an energy consumption as low as 1.6 kWh/m^3 through the use of a conservative system design composed of high-permeability RO membranes, a positive displacement high-pressure pump (HPP), and a positive displacement work exchanger ERD (Dundorf et al., 2007). For full-scale plants, energy consumption between 2.0 and 2.4 kWh/m^3 is typical, with full-plant energy consumption, including raw water pumping, pretreatment, chemical dosing, post-treatment, and residuals disposal typically around 3.3 kWh/m^3.

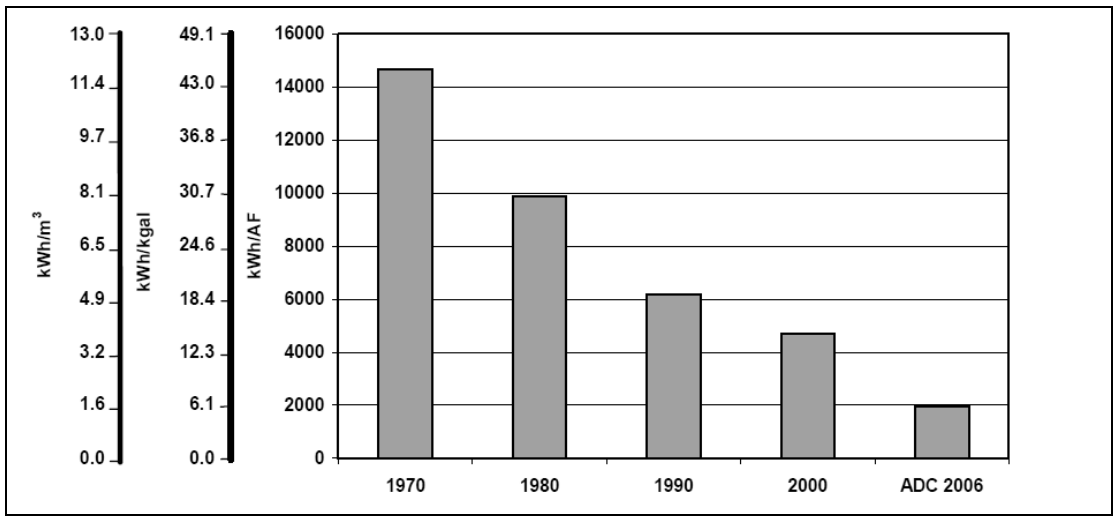

Figure 1.5. History of power consumption required for seawater desalination process equipment (Dundorf et al., 2007).

1.3 Use of Energy Recovery Devices in Desalination

ERDs utilized in RO applications convert residual hydraulic energy into mechanical energy that is reapplied either to the RO feed (for seawater applications) or to an interstage feed (for brackish or wastewater applications) in order to reduce the energy input to the RO system.

Two general classifications of ERDs are commercially available and utilized in the desalination industry: centrifugal devices and isobaric devices.

Centrifugal devices can further be classified into direct-coupled devices and turbocharger devices. Direct-coupled devices, including the Pelton Wheel and the Francis Turbine, are direct-coupled to the HPP and motor shaft. Rotational energy imparted to the turbine from converted concentrate pressure is directly transferred to the motor shaft, reducing the motor power requirements. The HPPs for a direct-coupled device are sized for the full feed flow and pressure; however, the motor power can be reduced as a result of the energy recovery.

In a turbocharger device, a turbine is direct-coupled to a pump impeller on a common shaft and located downstream of the HPP. Rotational energy imparted to the turbine from converted concentrate pressure is reconverted to pressure energy through the impeller and used to boost either the RO feed pressure (for seawater systems) or the interstage pressure (for brackish or wastewater systems). The HPP is sized for the full feed flow, but the head requirement is decreased by the boost pressure provided through the turbocharger.

For isobaric devices, a side stream of the low-pressure feed and the concentrate stream are directed to a positive displacement device. Energy from the concentrate stream is directly imparted into the feed stream. A small booster pump is typically required to raise the pressure of the side stream to the feed pressure. The HPP is typically sized for the permeate flow of the RO system and the full feed pressure. Isobaric devices typically have the highest efficiency of the ERDs, but require additional equipment, and may allow leakage between the concentrate and the feed/interstage streams.

Each of these devices is described in additional detail in Chapter 2.

Few independent evaluations of ERDs have been conducted to date. As a result, little comparative information is available to permit engineers and utilities to evaluate ERDs rapidly and easily for use in their facilities.

1.4 Report Organization

The objectives of this project are to create a thoroughly researched guidance manual that assesses currently available and emerging ERDs for desalination systems, and to create a computer tool including those commercially available ERDs for the treatment of brackish water, seawater, and wastewater effluent. This project was sponsored by the California Energy Commission and the WateReuse Foundation as part of the Foundation's Solicited Research Program. The U.S. Bureau of Reclamation is a funding partner for this project.

The report is organized into the following sections:

- Chapter 1, Introduction.
- Chapter 2, Literature Review—The literature review examines the history of energy recovery in desalination applications leading to the development of modern commercially available devices. Commercially available devices are reviewed and qualitatively compared. Several developing devices also are reviewed. Based on the results of the review, screening of the devices was conducted to determine the devices included in the model.

- Chapter 3, Model Development—Based on the screening study presented in Chapter 2, an Excel-based mass balance, RO projection, and cost model were developed. Chapter 3 reports on the model development, validation, and structure. A user manual is provided for the tool as well.
- Chapter 4, Case Studies—Case studies for five different utilities were conducted to evaluate the use of ERDs. Case studies were developed for two seawater, two brackish water, and one wastewater reuse facility. The individual case studies are presented in Chapter 4.
- Chapter 5, Conclusions and Recommendations

Chapter 2

Literature Review

With an expanding market for energy recovery, many of the commercially available ERDs utilize proprietary designs. Few ERDs have undergone third-party independent testing and analysis leading to the publication of a peer-reviewed paper. Much of the literature available is either vendor-produced, with obvious bias, or trade literature published by manufacturers or users. The authors have developed this literature review to provide an objective and unbiased technical review and assessment of the various ERDs available in the marketplace.

2.1 Methodology

This literature review incorporates published material from peer-reviewed journal articles, conference presentations and proceedings, patents, technical reports, user reviews, feasibility analyses, media reports, and information on vendor websites and brochures. To collect this literature, the key sources summarized in Table 2.1 were electronically searched for relevant information via publisher databases. Keywords used in the search included "reverse osmosis," "nanofiltration," and "energy recovery," which are related to all types of desalination.

Patent information related to ERDs was obtained by searching the U.S. Patent and Trademark Office database using the following keywords: "energy recovery," "reverse osmosis," "specific energy," and "desalination." This search yielded more than 50 relevant patent citations, from 1977 to October 22, 2010. Key patents were reviewed and are referenced in the sections that follow.

Table 2.1. Literature Review Sources

Peer-Reviewed Journals	Grey Literature	Conference Proceedings (previous 10 years)
Journal of Desalination Journal of Membrane Science International Water Association Water Science and Technology Water Science and Technology - Aqua Water Science and Technology: Water Supply Journal of Water Supply: Research and Technology - Aqua Water Research Desalination and Water Treatment Science and Engineering Journal American Water Works Association (AWWA) Journal of the American Institute of Chemical Engineering Journal of Chemical Engineering Research and Design International Desalination Association (IDA) Journal of Desalination and Water Reuse	Desalination and Reuse Quarterly Global Water Intelligence Water Desalination and Reuse Quarterly U.S. Patent and Trademark Database Vendor Literature Research Reports U.S. Bureau of Reclamation WaTER Studies Saline Water Conversion Corporation (SWCC) Studies Middle East Desalination Research Center (MEDRC) Studies American Water Works Research Foundation Research Reports WateReuse Foundation archives Texas Water Development Board Studies National Water Research Institute (NWRI) Studies	AWWA Annual Conference and Exhibition (AWWA ACE) AWWA Association Membrane Technology Conference (AWWA MTC) AWWA Water Quality Technology Conference (AWWA WQTC) American Membrane Technology Association Annual Conference and Exhibition (AMTA ACE) IDA Biennial Conference and Exhibition WateReuse Research Conference European Desalination Association Annual Conference

2.2 Energy Consumption in Reverse Osmosis

With increasing water scarcity, development of marginal or impaired water supplies for potable use has increased in both frequency and capacity. Marginal or impaired waters, such as wastewater effluent, brackish groundwater, and seawater, often contain multiple contaminants of concern, including TDS, organic compounds, and various emerging contaminants. Technologies used to treat these water supplies include desalination through nanofiltration (NF), electrodialysis, and most importantly, RO. RO is one of the predominant methods used to produce potable water from impaired waters.

Global growth in desalination of impaired waters has accelerated in the past decade, as illustrated in Figure 2.1 (International Desalination Association [IDA], 2010). The world-wide installed capacity, tracked by Global Water Intelligence (GWI), now exceeds 70 million cubic meters per day (m^3/d). Similar growth in application of desalination technologies has been tracked in the United States, as shown in Figure 2.2 (GWI, 2011).

Development of impaired waters in the United States has been focused on producing potable water from brackish water supplies. Brackish water desalination represents over 51% of U.S. desalination installations (GWI, 2011). In water-scarce regions, such as Arizona and California, large-scale wastewater reclamation projects using RO have been installed. One plant, the Ground Water Replenishment System, located in Orange County, California, has a capacity of more than 70 million gallons per day (mgd).

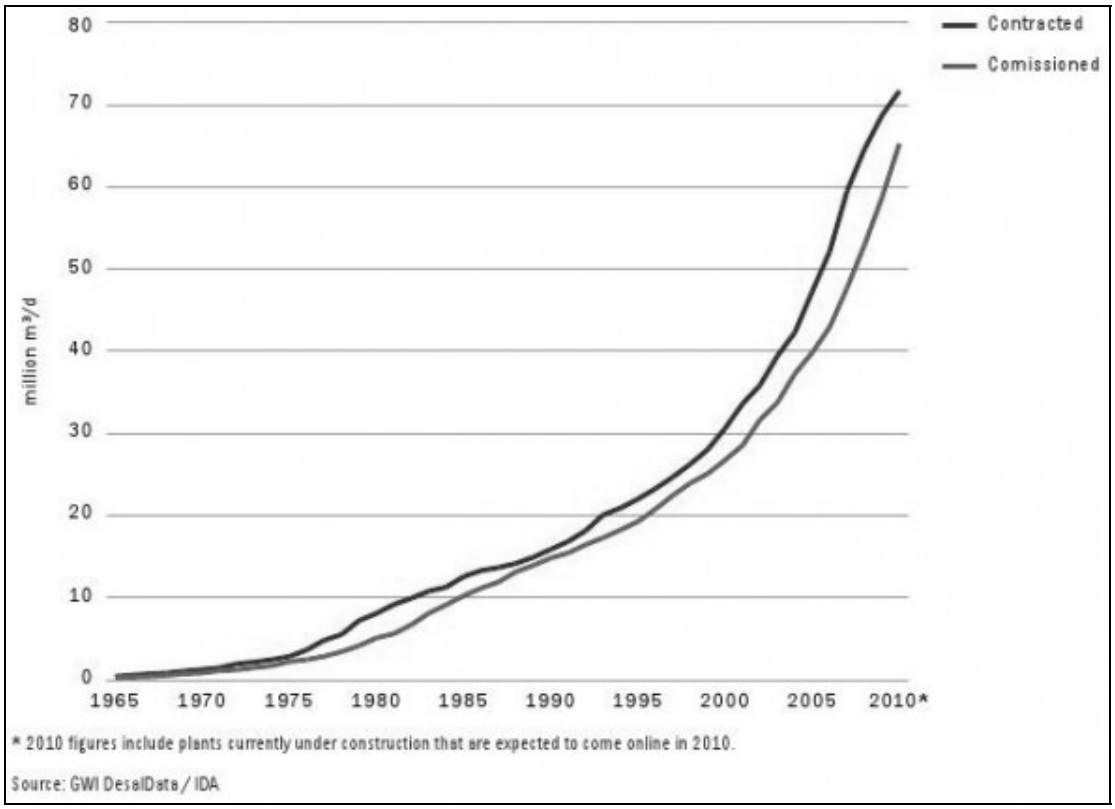

Figure 2.1. Global growth of desalination (seawater, brackish, etc.) between 1965 and 2010.

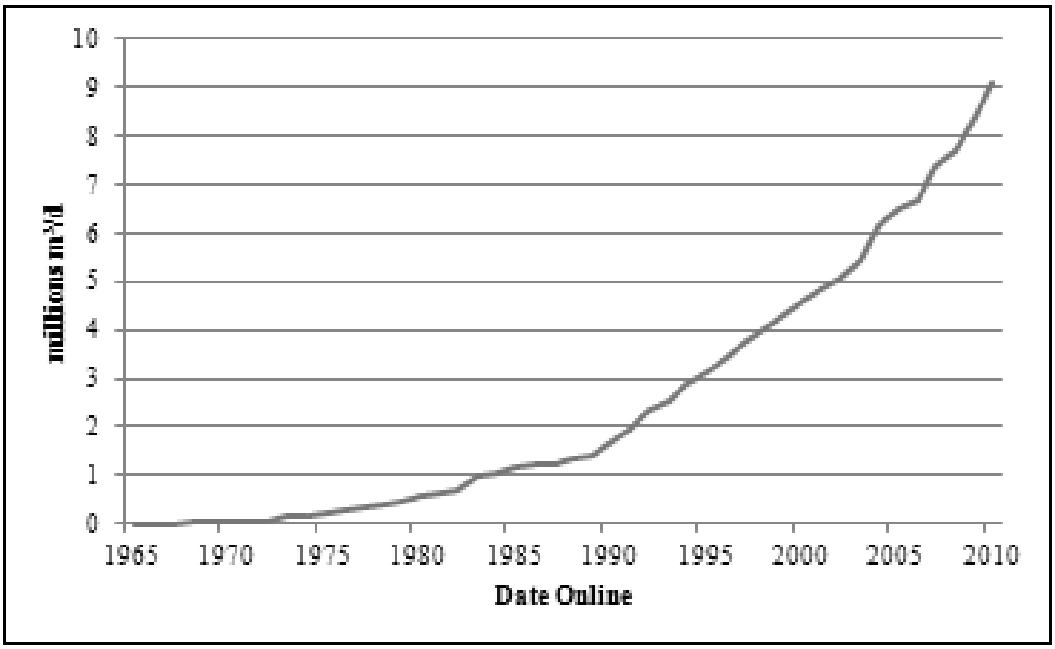

Figure 2.2. Cumulative online desalination (seawater, brackish, etc.) capacity in the United States, 1965–2010.

Seawater desalination is gaining interest as a method of further addressing projected water shortfalls in the United States, with one major SWRO facility currently in operation in southwest Florida (Tampa Bay). Significant opposition to seawater desalination plants has been mounted by various entities, particularly in California. One frequently cited reason for opposition is the high energy consumption of desalination plants, which, through increased greenhouse gas emissions, could impact climate change. The high energy consumption for RO-based seawater desalination, relative to desalination of brackish water and wastewater effluent as well as nondesalination technologies, is currently considered one of the primary obstacles to its expanded use in the United States.

Energy consumption in RO-based desalination is a function of several variables, including but not limited to

- Feed water TDS
- Water temperature
- System recovery
- Membrane flux
- Membrane mass-transfer coefficients
- Pump
- Motor variable-speed drive efficiencies
- Flow control valve losses
- Minor losses in system pipe work
- Use of ERDs

Energy use and recovery in a RO system differ for seawater and brackish/effluent applications.

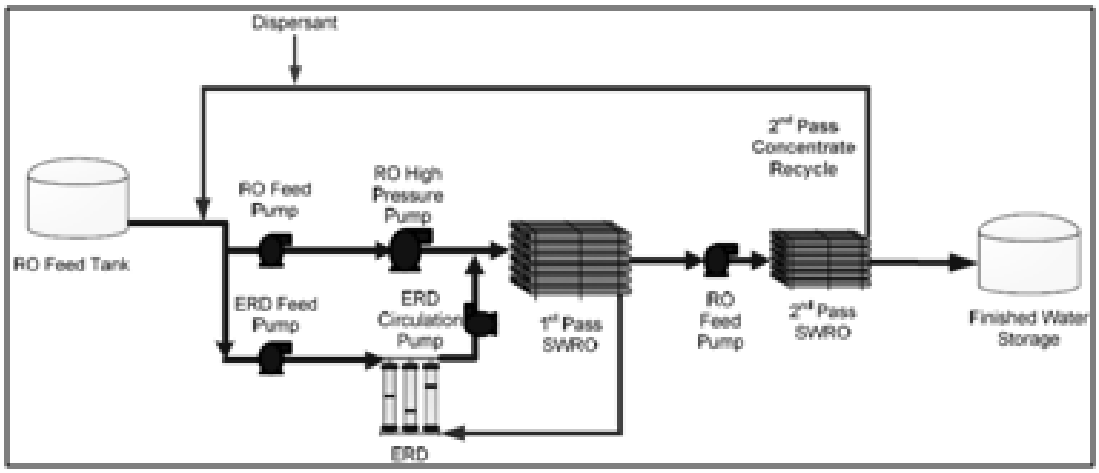

Figure 2.3. PFD of SWRO plant, Pilbara (CH2M HILL).

Figure 2.3 illustrates a typical SWRO desalination plant process flow diagram (PFD).

2.2.1 Methods for Measuring Energy Consumption and Recovery

Energy consumption values for water processes are typically reported in terms of specific energy consumption (SEC), which is calculated using the following equation:

$$\text{SEC} = \frac{\text{Total power consumed on an annual basis (kWh)}}{\text{Annual product water produced (m}^3\text{ or kgal)}} \tag{2.1}$$

However, the industry lacks standards governing how energy consumption is calculated or reported. Published values may include only the energy required for the desalination process itself, or for the whole facility. External loads, such as raw water conveyance and finished water pumping, may be excluded. For theoretical calculations, minor expected losses may be ignored entirely. It is also important to recognize, particularly in the international marketplace, that transparency in reported SEC is not ensured. This variation in how SEC is reported makes comparison of processes and technologies difficult.

Despite this, three common methods of calculating energy consumption stand out in the literature: direct accounting, exergy analysis, and visual analysis, specifically Sankey diagrams. Direct accounting produces theoretical SEC values based on flow rates, pressures, efficiencies, and estimated losses. These calculations are most commonly used to determine the operating and connected loads of a desalination plant. The results are then used by electrical engineers to develop the single-line diagram and design for the electrical subsystems for a plant. For operating plants, direct measurements of the voltage and amperage draw of the plant components can be recorded and used to calculate SEC. Ideally, the power-consuming components associated with desalination can be monitored separately to determine the SEC for the desalination process alone.

In academia, the concept of “exergy” is frequently applied. Exergy analysis relies on thermodynamic theory to quantify the minimum work required to complete a process and the additional work consumed as a result of increases in entropy (Spiegler and El-Sayed, 2001). Exergy is calculated using measured or theoretical salinity, pressure, and temperature

gradients at each unit process in a defined system boundary. This analysis is particularly valuable in evaluating the potential for energy reduction in each component of a desalination system and, thus, is useful to the desalination engineer. Exergy analysis has been applied to RO desalination by a number of researchers. For example, Cerci (2002) applied exergy analysis to a 7250 m^3/d (1.9 mgd) SWRO system in California. The total exergy required for desalination was 7.13 kW, with a total exergy input of 165.62 kW. Although much of the exergy consumed in the process is related to an expected pressure drop across the RO membrane interface, the exergy analysis showed that throttling of the brine stream pressure prior to discharge consumed considerable exergy. Introduction of an ERD was suggested as an energy-saving option to recover this available energy (Cerci, 2001).

Although exergy analysis is useful in the optimization of desalination processes and for calculating theoretical available energy for recovery, few engineers involved in desalination are familiar with exergy analysis. Therefore, exergy is of limited practical interest in most desalination applications.

Sankey diagrams also have been used to illustrate the transfer and flow of energy through a system. These diagrams use a separate line for each process flow and energy loss in the system. The width of each line denotes the relative energy utilized or lost in each process. Although a Sankey diagram does not indicate the potential for additional energy savings in each stream, it clearly communicates the energy used in each stream and the losses associated with each component. It is important to note that energy flows depicted in a Sankey diagram are not the same as exergy calculations. Figure 2.4 is a typical Sankey energy balance for a small SWRO system using a Clark Pump ERD to capture energy otherwise lost in the pressurized brine stream (Thomson et al., 2002).

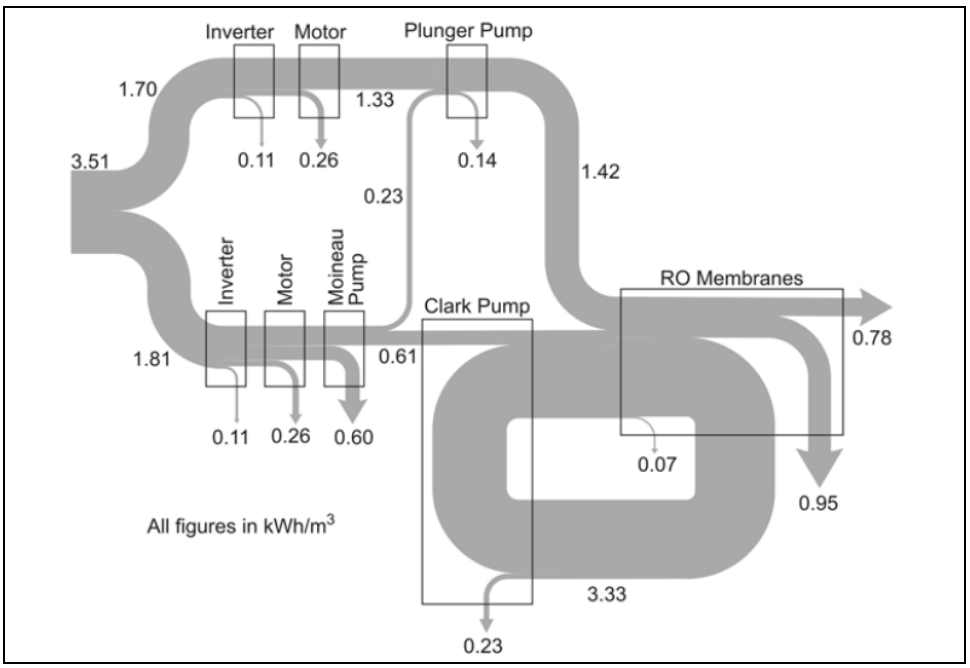

Figure 2.4. Example of Sankey diagram—SWRO system with Clark Pump (Thomson et al., 2002).

To meet the increasing demand for freshwater in the global energy crisis, the desalination industry is being pushed to improve the operational efficiency of the SWRO desalination

system (Sun et al., 2008). Exergy analysis, Sankey diagrams, and other calculations in the literature show that the greatest opportunity to improve efficiency is implementing energy recovery from the brine stream. The need to develop efficient ERDs has therefore been the aim of many scientists and engineers since the 1970s.

2.2.2 Energy Consumption of Seawater Reverse Osmosis Plants

Desalination of seawater has historically been perceived as an expensive process because of its high energy demand. Early SWRO plants consumed between 12 and 15 kWh/m^3, depending on salinity, temperature, and other conditions (Plascencia, 2002; Veerapaneni, 2006). Because of high SEC values, almost half of the total cost of desalting water was the cost of energy, especially for small-scale SWRO desalination systems (Avlonitis et al., 2003).

Table 2.2 summarizes energy consumption for a number of seawater desalination systems.

2.3 History and Modern Development of Energy Recovery Devices

2.3.1 History of Energy Recovery

The history of recovering energy from high-pressure streams significantly predates membrane-based desalination. The first successful turbine was introduced in France by Benoit Fourneyron in 1829. This radial-flow turbine improved upon early turbines used in early industrial applications. Development of turbines, or reverse running pumps, continued throughout the nineteenth century, with new designs tested and introduced in the United States. The most notable design, because of its high efficiency, was introduced by James Francis in 1848. The Francis Turbine, also referred to as a reverse running pump, recovers energy from high-pressure streams by rotating a direct-coupled central shaft. Refined models of the Francis Turbine are still in use today (Constant, 1983; Darwish et al., 1989).

Independent of Francis Turbine development, the high energy needs of the California Gold Rush of the mid-1800s spawned the development of new water wheel devices to extract hydraulic energy. Lester Pelton experimented with paddle geometry and ultimately developed new water wheel paddles that captured more of the velocity head wasted by earlier turbine designs. Pelton received a patent in 1880 for the Pelton Wheel, illustrated in Figure 2.5 (Pelton, 1880; Constant, 1983).

Significant development of impulse turbines continued into the twentieth century. By the time Sidney Loeb patented the modern RO membrane in 1964 (Loeb and Sourirajan, 1964), both the Francis Turbine and the Pelton Wheel were highly refined and widely used in industry to recover hydraulic energy. Shortly after Loeb's discovery, work exchanger or isobaric device patents related to the recovery of hydraulic energy in the chemical processing industry were filed by Swaney (1961) and Ross (1963). The first piston work exchanger to be used with RO technology was invented by Cheng and Cheng (1970), with a later rotary design by Hashemi and Lott (1969).

Table 2.2. Examples of SWRO Plant Energy Consumption

Plant	Date of Estimate	ERD Technology	Total Plant Power Consumption [a]		Capacity	
			kWh/m^3	kWh/kgal	m^3/d	mgd
Tampa Bay Desalination Plant, U.S.A.	2008	PIT	3.71	14.0	94,625	25
Barcelona, Spain [b]	2009	PX	4.17	15.8	200,000	53
Perth I (actual), Australia	2008	PX	3.4	12.9	143,000	37.78
Perth I (design), Australia	2008	PX	3.7	14.0		
Larnaca, Cypress [c, d]	2001	PIT	4.35 (3.4 RO)		64,000	17
Ashkelon, Israel	2009	PX	3.9	14.8	333,080	88
Pt Lisas, Trinidad	2007	DWEER	3.80	14.4	136,260	36
Gold Coast, Australia [e]	2010	DWEER	3.58	13.5	131,952	35
Sydney, Australia	2008	DWEER	4.2	15.9	250,000	66.05
Ghalilah Unit 3, U.A.E. [f]	2005	PX	4	15.1	13,650	3.60
Tuas, Singapore [g]	2010	DWEER	4.1	15.5	110,000	29

[a] PIT = Pelton Impulse Turbine; PX = Pressure Exchanger; DWEER = Dual Work Exchange Energy Recovery

[b] RO system power consumption is included in Total Plant Power Consumption.

[c] Water-technology.net "Barcelona Sea Water Desalination Plant, Spain."

[d] Larnaca Desalination Plant Operation—A Client and Contractor Perspective, Koutsakos et al., 2005. Water-technology.net "Larnaca SWRO."

[e] Water-technology.net "Gold Coast Desalination Plant, Queensland Australia."

[f] Stover et al., 2007 Includes 6 bar product water distribution pressure,

[g] Water-technology.net "Tuas Seawater Desalination Plant - Singapore."

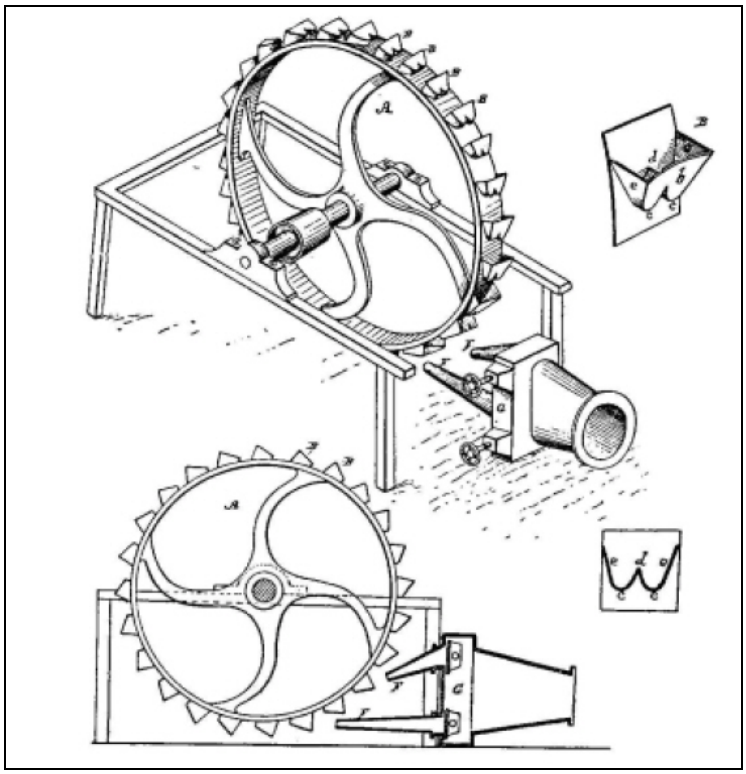

Figure 2.5. Pelton Wheel patent drawing (Pelton, 1880).

From these early devices, modern ERDs have evolved into two major categories:

- *Centrifugal Devices.* Centrifugal devices include various improvements and adaptations of the Pelton Wheel and Francis Turbine. Centrifugal devices may be coupled to a separate pump and motor shaft or directly coupled to a pump shaft to provide auxiliary pressure boost without the use of a pump. Centrifugal devices that are direct-coupled turbine–pump combinations are typically referred to as turbochargers.
- *Isobaric Devices.* Work exchangers are positive displacement devices, typically using two or more chambers or pistons, with or without a moveable plenum, to transfer energy from a concentrate to a feed. Work exchangers may be either stationary piston- or rotary-type devices. Stationary piston work exchangers, such as Flowserve/Calder's Dual Work Exchanger Energy Recovery (DWEER), utilize proprietary valving to sequence the flows through the device. Rotary work exchangers contain a number of different chambers within a cylinder. As the cylinders rotate, driven by water flow or an external motor, the cylinders change position relative to the inlet and outlet ports, thereby sequencing the flows through the device.

There have been several additional developments in energy recovery that are not adequately addressed by the two major categories. These devices differ by mechanism or output from the centrifugal and isobaric devices, and they are discussed in more detail in Section 2.3.3.

The modern development of each class of device is discussed separately. Devices chosen for further analysis and model development are further described in Section 2.3.3.

2.3.2 Modern Development of Centrifugal Devices

Modified Francis Turbines and Pelton Wheels increased efficiency and adoption in early SWRO facilities. The first large municipal SWRO incorporating Pelton Wheel technology was installed in Jeddah, Kingdom of Saudi Arabia, in 1978 and required 6.1 kWh/m^3 of energy. In the West, the first RO desalination plants to adopt ERD technology included facilities installed in the early 1980s in Key West, FL; Paradise Island, Bahamas; and the island of Malta (Moch and Harris, 2002). These facilities used a simplified Francis Turbine, an early version of a Pelton Wheel, and a more sophisticated Francis Turbine, respectively. Energy recoveries in these early adopting plants were about 25% of the RO input energy.

In 1978, a U.S. patent was granted to Everett Schwartzman for a direct-coupled Pelton Wheel device (Schwartzman, 1978). With a direct-coupled Pelton Wheel, the HPP, motor, and ERD are mounted on a common shaft. The ERD directly transfers recovered energy to the pump shaft, allowing a much smaller electric motor to be installed on the incoming stream. This device has been widely applied in seawater desalination, including modern plants such as the Tampa Bay Desalination Plant in Florida.

With attention focused on work exchanger devices, the next major development in centrifugal energy recovery was the turbocharger. Introduced in the 1980s by the brothers Robert and Eli Oklejas, the turbocharger is an integral turbine-driven centrifugal pump that transfers hydraulic energy from the concentrate to the feed stream. The system is entirely powered by the brine stream and has no electrical cooling or pneumatic requirements (Farooque et al., 2004). Field testing of an early prototype turbocharger in conjunction with a military SWRO system showed energy recovery efficiencies in the range of 17% to 29% (Lozier et al., 1989).

The first patent for a turbocharger was granted in 1990 to Robert and Eli Oklejas, who successfully commercialized the devices under Pump Engineering, Inc. (PEI) (Oklejas et al., 1990). In the early 1990s, PEI developed and patented three other designs that used power recovery pump turbine systems to recover energy from RO concentrate (Oklejas et al., 1991a, 1991b, 1992). Eli Oklejas went on to found the Fluid Equipment Development Company (FEDCO) in 1997, which also produces turbocharger devices. Under PEI, Robert Oklejas (2000) continued developing turbochargers and received a patent specifically designed for improving efficiency of a RO system. Several of FEDCO's and PEI's devices are discussed in further detail in Section 2.3.3.

Centrifugal devices offer maximum net transfer efficiencies of around 88% at the optimum design point. To optimize ERD performance and obtain the high efficiency necessary for cost-effective operation, SWRO plants were designed and operated at fixed water recovery rates—typically 45% for Mediterranean Sea and 35% for Arabian Sea waters (Stover et al., 2007). Modern commercial centrifugal devices are discussed in further detail in Section 2.4.

2.3.3 Modern Development of Isobaric Devices

This section describes early work exchangers, which were developed after centrifugal devices and made use of positive displacement via externally driven rotary displacement or stationary pistons, as well as several emerging isobaric devices that are patented but not yet commercial.

2.3.3.1 Rotary Work Exchangers

Following the early rotary work exchanger devices described previously (Swaney, 1961; Ross, 1963; Hashemi and Lott, 1969), significant advances have resulted in several commercialized devices that have similarities to the modern rotary work exchanger, including those by Hauge (1989, 1994, 1999). Hauge's early designs are known for metal components, which were later replaced with more durable ceramic.

Hauge (2003) developed and patented a system where a rotary work exchanger is used to transfer pressure energy from one flow to a second flow. The device consists of two end covers, a rotor, and a rotor liner that are mounted together via a center bolt in a pressurized housing. In this configuration, elastic deformation, essentially tensile stress, was reduced and the exchanger was protected from internal impact. These later designs are commercialized as Pressure Exchangers (PX) by Energy Recovery Inc. (ERI).

Several other rotary work exchanger devices have been patented but have not been placed in commercial production or application (Al-Hawaj, 2004; Brueckmann et al., 2005; Herrington and Hand, 2007; MacHarg, 2010). These advances are notable as they seek to address the shortcomings of commercially available devices.

Al-Hawaj (2004) patented a rotary work exchanger device with a freely moving spherical bearing in each internal chamber. This design reduced mixing in the rotating chambers, which slightly reduces the efficiency of traditional pressure exchangers.

Brueckmann et al. (2005) also patented a pressure exchanger system with at least two tubular chambers; in each chamber, several valves reverse the flow paths of high- and low-pressure fluid flows.

Herrington and Hand (2007) patented a combined ERD and pump device (assigned to MIOX Corporation). The device combines a dual-head reciprocating pump, an RO element, and a differential-pressure-activated valve, which offsets fluid pressure on the two pump heads and generates energy recovery (Herrington et al., 2007).

The most recently patented device is a combined axial-piston liquid pump and energy recovery pressure exchanger system developed by MacHarg (2010). This device comprises a pumping machine for pressurizing a primary liquid flow, a rotor-drum-type axial piston pump (APP), and an isobaric work exchanger that recovers energy from a secondary liquid flow. The system has benefits including fewer moving parts, small machine size, and lower capital and operating costs. This device is currently being commercialized as the Ocean X pressure exchanger.

2.3.3.2 Piston Work Exchangers

The first work exchanger device that employed stationary pistons was a design patented by Cheng and Cheng (1970). In 1971, another study was funded by the Office of Saline Water, now the U.S. Bureau of Reclamation, in which Cheng and Cheng examined piston- and bladder-style work exchangers. These early piston-type work exchangers experienced significant issues with valving, including erosion, wear, and pressure variations. Keefer (1984) developed and patented a volume exchange structure to minimize these impacts. Keefer's piston-type RO booster pump had several cylinders, each with a displacer rod

carrying a displacer to divide the cylinder into pumping and expansion chambers to enable energy recovery.

Prior to the 1990s, most of the emphasis on and use of ERDs was associated with larger desalination systems. Gray (1996) and Permar (1997) patented portable water purification systems with hand-powered double-piston pumps. These devices are not commonly applicable to large-scale units because of fluctuations in flow and pressure. However, they are widely used on seagoing vessels as emergency devices for life rafts.

In 1998, Shumway patented the Linear Exchanger (LinX) valve while working for DesalCo Limited. This valve improved reliability, reduced maintenance requirements, and allowed for faster valve switching in piston work exchanger devices. LinX reduced the size and cost of ERDs such as the DWEER (discussed in Section 2.4).

Another innovation, the integrated pumping and energy recovery (IPER) system, also known as VARI-RO, was patented by Childs and Dabiri (2000). Child and Dabiri's system includes two cylinders with pump-driven pistons and was designed to overcome the limitations caused by fluctuations in flow and pressure experienced by other types of devices. In its operation, the hydraulic pump drives the common piston shaft to provide energy recovery and pumping.

El-Sayed et al. (2010) recently patented a new pressure exchange apparatus that increases the number of internal chambers typically present in a piston-type device.

Axial piston pumps, such as the device manufactured by Danfoss, are positive displacement pumps that have a variable stroke length, also known as swash plate pumps. These pumps have been operated successfully in reverse as ERDs. Danfoss has also introduced its iSave product, which combines an isobaric pressure exchanger with septum and an integrated vane pump to make up the losses in the high-pressure circuit of an RO system.

2.3.3.3 Emerging Isobaric Devices

There are a number of emerging ERDs, which are defined here as technologies that have very limited, if any, existing full-scale desalination applications. These emerging ERDs include the following products:

- VARI-RO
- RO Kinetic
- Hydraulic Energy Recovery (HER)
- Rotary Work Exchanger (RWE)
- Fluid Switcher Energy Recovery Device (FS-ERD)
- Rotary Isobaric Device APP

VARI-RO, the IPER system patented by Childs and Dabiri (2000), does not require external main and booster pumps, significantly simplifying installation. There are different versions of the VARI-RO IPER system, including VARI-RO EL (electric drive), VARI-RO ST (steam turbine drive), VARI-RO HR (heat recovery engine), VARI-RO NG (natural gas engine), and VARI-RO GEN (electric power generation). The last is an engine version that can provide the benefit of generating electric power (Childs and Dabiri, 1992, 1994, 1995).

Childs and Dabiri (1997, 1999) reported on the results of a VARI-RO unit tested using funding provided by the U.S. Bureau of Reclamation. During the two-year program, a prototype was designed, manufactured, and tested, demonstrating that the VARI-RO system was suitable for product water train capacities from 120 to 19,000 m^3/d (0.030 to 5 mgd). Childs and Dabiri reported that an energy savings of 20% to 50% can be projected, as compared to present commercially available methods for both SWRO and brackish water RO (BWRO) desalination. Purported benefits of the IPER system also include low cycle speeds, low noise, and reduced electric power surges on startup. The device is designed to operate at a single recovery, limiting the ability to vary recovery with changing feed water quality to manage energy consumption. Overall, no known sizable installations exist to date, and VARI-RO IPER systems have not yet been produced on a commercial scale. VARI-RO, Inc. had been contracted to provide a full-scale prototype for the Catalina Island desalination plant for Southern California Edison, but it has not been installed to date.

Several developing technologies could eliminate typical active mechanical devices in the recovery of energy. One of these developing technologies, the RO Kinetic pressure exchanger, is designed in a continuous closed loop or kinetic cycle. RO Kinetic, based in the Canary Islands, Spain, has a relatively small experience base and there are no known large-scale installations of the RO Kinetic ERD. However, there are several medium RO desalination plant installations. The two largest installations are the El Confital SWRO desalination plant and the El Fraile SWRO desalination plant, located on Tenerife in the Canary Islands. The El Confital SWRO plant has a nominal production capacity of 4000 m^3/d and has been reported to achieve a SEC of 2.13 kWh/m^3. The El Fraile SWRO desalination plant has a nominal production capacity of 1800 m^3/d, and the plant has been reported to achieve a SEC of 2.25 kWh/m^3 (Peñate et al., 2010).

Marketing literature claims a potential reduction in SEC to 2.10 kWh/m^3 using the RO Kinetic ERD, compared with conventional turbine-type ERDs in optimized facilities with SECs of 3.50 to 4.00 kWh/m^3. An efficiency of approximately 98% is reported. Because of minimal throttling and rotating equipment (typically fewer than five cycles per minute), the reported noise level produced by the RO Kinetic is negligible. This is advantageous because noise and/or vibrations often cause failure from fatigue in the materials of the system or in the rest of the plant (Plasencia, 2004) or require design changes in the facility to address health and safety concerns. There are no reports in the literature regarding the size and volume of the loops and the additional space requirements for the RO Kinetic ERD. Marketing literature does state that the system is a "very versatile installation with no need of great space requirements [and] can be installed in very diverse ways (vertically, horizontally, under the RO skid, in parallel to the skid or integrated into the skid structure)." As with all other ERDs, higher capacity is achieved by operating multiple units in parallel (Plasencia, 2002).

Several new ERDs have been developed in academia, including the HER, RWE, and FS-ERD. The HER device is very similar to the Clark Pump (Thomson et al., 2002) and the pressure exchanger–intensifier (Folley et al., 2008), except that the directional valves of the HER device are installed within the device and driven by the pistons. Because the switches of the directional valves belong to an instantaneous process, the pressure surges during the switches can be effectively weakened or even eliminated (Sun et al., 2008). The inventor claims a high-pressure transfer efficiency of approximately 94%. Simulated results show that the HER device can decrease the SEC of the SWRO system from 10 kWh/m^3 to 3.0 kWh/m^3.

The RWE is purported to be a compact variable-flow, positive-displacement pump and energy recovery system for SWRO and BWRO desalination. Similarly to ERI's PX, the

pressure from the concentrate stream is used to rotate a cylinder containing multiple channels. Unlike the PX, the RWE provides a physical barrier between the feed water and concentrate. A single needle valve controls the rate of rotation of the device (Al-Hawaj, 2003). Although no working prototype has been described, the inventor purports that the RWE has simpler control requirements and lower mixing than other isobaric devices available on the market. As with most devices, an external booster pump is required to offset energy losses through the RO feed spacer and system piping.

In an attempt to improve upon existing two-cylinder isobaric ERDs, Tianjin University in China has developed the FS-ERD. The FS-ERD is composed of four portions: a rotary fluid switcher, two pressure cylinders, and a check valve nest. The core component is the rotary fluid switcher, which has four joint ports and two working phases, similarly to a two-position four-way valve. A piston installed in each cylinder isolates seawater from brine and ensures minimum mixing during operation. The position of the piston is detected to determine whether the pressurizing or depressurizing stroke has been accomplished and when the fluid switcher should be changed to the next working phase. Under this condition, the high-pressure brine stream is imported into Cylinder 1, and the prefilled low-pressure seawater feed is pressurized and pumped out; this is called the pressurizing stroke. Simultaneously, the high-pressure brine stream in cylinder 2 is depressurized and drained out by the incoming low-pressure seawater feed, called the depressurizing stroke. Thereafter, when the FS-ERD accomplishes its pressurizing stroke (and also its depressurizing stroke), the switcher rotates to working in the second phase at a low speed of 7.5 revolutions per minute (rpm), driven by a motor, which denotes that the stroke modes in cylinders are alternated (Wang et al., 2010). No known sizable installations exist to date, and the FS-ERD has not yet been produced on a commercial scale. However, a bench-scale demonstration of parallel FS-ERDs is in progress with a capacity of 2×500 m^3/d under typical SWRO operating pressure (Wang et al., 2010).

Based on typical product development timeframes, potential commercial application of these developing technologies is likely 5 to 10 years in the future.

The introduction of the more efficient isobaric devices, combined with improvements in pump/motor capacities with flat operating curves and membrane/element innovations, has lowered the energy consumption of a typical SWRO to 3.5 kWh/m^3 (Truby, 2006). In the opinion of a number of authors, isobaric devices became the most efficient ERDs on the market for SWRO plants (Hauge, 1995; Geisler et al., 1997; Andrews and Shumway, 1999; Kiang et al., 2005; Stover, 2007).

Most of the large SWRO plants being designed and built today utilize isobaric ERDs. With modern isobaric ERDs, efficiencies as high as 97% can be obtained over a range of membrane water recovery rates and/or feed water salinities. Consequently, energy consumption has been reported as low as 2.7 kW/m^3 (Sanz and Stover, 2007).

MacHarg (2011), through funding provided by the Texas Water Development Board, investigated the use of isobaric energy devices in BWRO applications. A pilot study was conducted at the Kay Bailey Hutchison Desalination Plant in western Texas. It was anticipated that the isobaric ERD could be applicable to the BWRO marketplace. Because of the difference in membrane configuration from single-stage SWRO systems, the isobaric ERDs would need to be configured differently as well. The pilot study demonstrated that the isobaric ERD could be successfully incorporated into the BWRO systems. The optimum operating point was at 80% energy recovery and the feed water had a TDS of ~3500 mg/L..

Full-scale model extrapolations to a 3-mgd RO train determined a 1.59 kilowatt-hours (kWh) per 1000 gallons SEC.

Brine-to-electricity is a generic term for systems that produce electricity from concentrate pressure, similarly to hydropower. This has been successfully used with low-pressure turbo devices and with Pelton Wheels. Generating asynchronous electricity allows the ERD system to rotate at peak efficiency speeds, unencumbered by the need to match a pump or motor speed. Additional electrical equipment is required to manage the electric load, match frequencies, and utilize this energy in the system.

2.3.4 Summary

Energy transfer efficiency as high as 90% can be achieved using work exchanger or positive-displacement-type devices. On the other hand, centrifugal devices are only able to achieve efficiencies of 50% to 75% (Andrews et al., 2001; Moch and Harris, 2002; MacHarg, 2002; Wang et al., 2010).

SWRO plants are currently being established around the world, with ever-increasing capacities (Wang et al., 2010). The power required to drive the HPP(s) is typically the largest component of the operating cost of these SWRO systems. To satisfy the increased needs of SWRO plant capacity, many enhancements have been put into practice, including increased ERD per unit size and parallel ERD facility operation (Kronenberg, 2002; Schneider, 2005). Parallel operation is considered to be the most promising, as this operation mode increases the ERD's capacity while having the potential to significantly reduce or even eliminate fluctuations of the ERD working streams (Sun et al., 2008). In a review of the desalination market, Henthorne (2004) indicated that the cost of desalting water has reached an all-time low of about \$0.50/m^3, driven largely by increased installed capacity (economies of scale) and enhanced energy recovery.

Although energy consumption has been significantly reduced by the use of ERDs, improvements in membrane science have also contributed to this reduction. Gorenflo (2006) reports that membrane productivity has increased from 6000 to 9000 gpd. Productivity has increased past 9000 gpd and additional increases promise to further decrease the cost and energy consumption of desalination systems.

On the other hand, advances in ERD technology have not translated well to small-scale SWRO systems with less than 10 m^3/d of permeate production. Such small plants typically do not utilize ERDs to decrease the overall capital cost, but have SEC as high as 15 to 20 kWh/m^3 (Oklejas and Pergrande, 2000; Thomson et al., 2002). The payback period for installation of an ERD is much longer than with larger systems. To reduce relatively high operating costs, most existing small-scale SWRO systems are powered by renewable energy systems and grid-supplied energy. The absence of an ERD increases the amount of energy required to power desalination systems, and thus results in a very high water production cost (Tzen et al., 2003).

Table 2.3. Commercially Available Energy Recovery Devices

Manufacturer	Device Type	Trade Name	Capacity Range (m^3/d) per Device*
Flowserve/Calder	Centrifugal	Pelton Wheel	360 to 24,000
PEI (division of ERI)	Centrifugal	Turbocharger	136 to 65,500
FEDCO	Centrifugal	Turbocharger	360 to 84,000
Danfoss	Isobaric	iSAVE	504 to 960
Energy Recovery Inc.	Isobaric	PX	109 to 1,640
Flowserve/Calder	Isobaric	DWEER	2,400 to 8,450
Aqualyng	Isobaric	Recuperator	Proprietary
Spectra Watermakers	Isobaric	Clark Pump	<10
Spectra Watermakers	Isobaric	Pearson Pump	24 to 40
KSB	Isobaric	SalTec	Up to 20,000

*Note that the DWEER and ERI devices are easily operated in parallel for larger capacities.

2.4 Commercially Available Energy Recovery Devices

Currently, there are a limited number of ERDs responsible for over 90% of the total market share for SWRO systems. Isobaric devices, in particular ERI's PX and Flowserve/Calder's DWEER, are being installed in the majority of new facilities, particularly in energy-conscious environments. Where lower levels of energy efficiency are acceptable, turbo devices by PEI or FEDCO or the Flowserve/Calder Pelton Wheel are being installed. Other manufacturers, including Aqualyng and KSB, have minority stakes in the energy recovery market.

Table 2.3 summarizes the major commercially available ERDs. Each device type is discussed in additional detail in the remainder of this section.

For BWRO and reclaimed wastewater RO systems, nearly all ERD market share resides with turbocharger ERDs because of the better applicability of these devices to brackish water system configuration. However, there are a few exceptions; for example, the largest BWRO plant in the world, in Yuma, AZ, uses a Pelton Wheel.

2.4.1 Centrifugal Energy Recovery Devices

Although over 98% of ERDs installed in SWRO plants worldwide in 2000 were centrifugal devices, relatively few devices are commercially available. The lack of growth in this device type is due to greater advancement and higher efficiencies for isobaric devices. Still, the Francis Turbine, Pelton Wheel, and various turbocharger devices are still available for energy recovery applications.

The Francis Turbine, also known as a reverse running pump, is one of the oldest and most developed ERDs (Darwish et al., 1989). Because of its simplicity and ease of operation, the Francis Turbine quickly gained wide acceptance by SWRO industries. Francis Turbines are designed and sized to specific flow or pressure levels; thus, the pressure and flow range at

which such a system runs with maximum efficiency is very narrow. Variations in pressure or flow and/or changes to operation mean that the Francis Turbine must be bypassed, resulting in efficiency losses (Goubeau and Guinard, 1985; Kundig and Lineiro1997; Stover, 2007). Also, the device generally does not generate power until 40% of the design condition is achieved (Moch, 2000). Overall, Francis Turbines have overall efficiency (maximum efficiency around 75%) lower than that of competing isobaric devices (91% to 96%).

Many existing medium- and large-scale SWRO plants use Francis Turbine technology. The 50,000 m^3/d Fukuoka SWRO Desalination Plant in Japan operates at a recovery of 60%. Several plants installed in Saudi Arabia before 2000 incorporate Francis Turbine ERDs, including facilities in Jubail, Yanbu, Duba, and Haql (Nada et al., 1995; Al-Kutbi and Baig, 1998). With further improvements in other ERD technologies, Francis Turbines are less likely to be installed in new plants (Moch, 2000; Manth et al., 2003).

A Pelton Wheel, commercially available through Flowserve/Calder, relies on the same impulse turbine principles described for the Francis Turbine. In its operation, the high-pressure concentrate is fed into the Pelton Wheel hydraulic impulse turbine, which then produces rotating power output to assist the main electric motor in driving the main HPP. The system consists of an adjustable input nozzle to convert water pressure into kinetic energy contained in a high-velocity jet (Darwish et al., 2007). Energy recovery starts at about 40% of system pressure. The inlet nozzle acts as a brine control valve, and no further pressure control is used on the RO system. The Pelton Wheel is illustrated in Figure 2.6, and design and operational characteristics are summarized in Appendix A.

Some authors report that the Pelton Wheel is a more economical ERD than the Francis Turbine (Inglesias, 1999), with some installations achieving an efficiency between 80% and 90% (Heckel and Stern, 2002). Some also report that the efficiency stays relatively high over the full operational range, including changes in flow and pressure (Scholl, 1997). However, other authors report that these units suffer from loss of efficiency, especially when operating in the off-duty range (Goubeau and Guinard, 1985; Kundig et al., 1997; Manth et al., 2003; Stover, 2007) or when not properly designed and installed in the RO plant (Oklejas and Manth, 2002). Stover (2004) reported that Pelton Wheel efficiencies typically range from 40% to 60%, but efficiencies as high as 81% can be achieved for 90% efficient devices coupled to 90% efficient pumps. Flowserve/Calder has recently reported that its Pelton Wheels can achieve efficiencies as high as 90%.

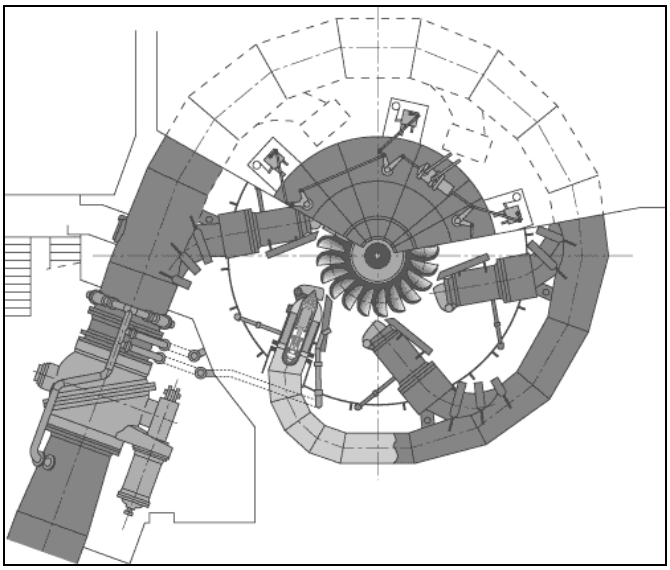

Figure 2.6. Schematic of Pelton Wheel.

Last, commercially available turbochargers are currently the most commonly applied centrifugal technology because of high-efficiency improvements. Turbochargers include a turbine portion (a single-stage radial inflow type similar to a reverse running pump) and a pump portion (a single-stage centrifugal pump with the impeller mounted on the turbine shaft). FEDCO and ERI offer turbochargers under the brand names Hydraulic Pressure Booster (HPB) and Turbo, respectively. A turbocharger device is illustrated in Figure 2.7.

FEDCO's Hydraulic Energy Management Integration (HEMI) is a turbocharger with the addition of motor and control logic to control system recovery and recover concentrate energy. The HEMI allows additional energy to be added to what has just been recovered from the concentrate, overcoming other losses in the system, such as membrane pressure drop, without the need for an additional, separate, booster pump.

Because performance is affected by variations in flow and pressure (Kundigand Lineiro, 1997; Stover, 2007), turbochargers typically have a bypass that enables the operator to control and balance flow. This bypass is needed when second-stage brine flow is above the level required for boost pressure, especially when the feed is subjected to large temperature variations, such as are typically seen in surface intake plants and/or for membrane aging (Farooque et al., 2004*)*. The device has a maximum possible efficiency of up to 85%, which is low compared to competing devices with top efficiencies of 91% to 96%.

The first commercial SWRO unit utilizing a turbocharger was sold in 1991 to Watersource, a Miami-based RO system builder, and installed in a U.S. Virgin Islands plant with a feed water flow of 150 gallons per minute (gpm) (9.5 liters per second [L/s]). Also, in 1991, two turbochargers were sold to be installed on Chiyoda's liquid natural gas project on Das Island, near Abu Dhabi. When commissioned, the plant produced 648 m^3/d (0.17 mgd) of permeate using DuPont's B-10 Twin Permeators per train operating at 65.5 bar (950 psi) and 34% recovery operating at an estimated SEC of 3.4 kWh/m^3 (12.9 kilowatt-hours per kilogallon [kWh/kgal]).

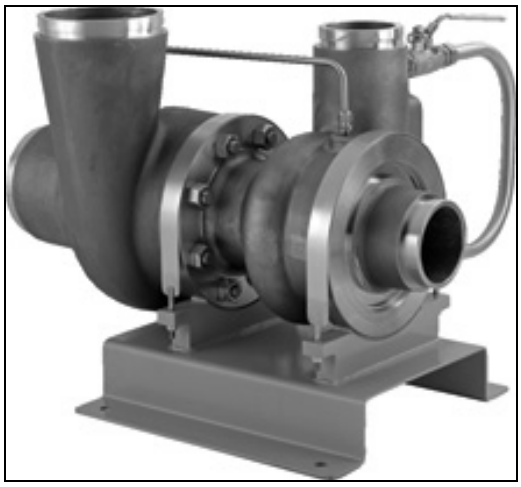

Figure 2.7. Hydraulic turbocharger.

Turbochargers are mainly used in conjunction with brine conversion systems (BCS) to increase water recovery up to 60%, with minimal increases in cost (Kihara et al., 2002). Vedavyasan (2002) reported that turbocharger installation in a SWRO plant can result in water cost reduction of 23% and a reduction in energy use of 18%. Overall, the hydraulic turbo charger–BCS system is reported to achieve an efficiency of about 70%, depending on capacity (Uchiyama et al., 1999).

The Magtaa SWRO, located on the Mediterranean coast of Algeria, produces 500,000 m^3/d using PEI HTCAT-7200 turbochargers (*Water and Desalination News*, October 2009). Medium BCS system plants are also being successfully operated in the Caribbean Islands (14,800 m^3/d) and at Mas Palomas, Gran Canaria, Spain (20,400 m^3/d) (von Gottberg et al., 2002). There are several small plants, built before 2000, with capacity ranging from 210 to 5,700 m^3/d that utilize a turbocharger–BCS system (Moch, 2000).

The design and operational characteristics of turbocharger devices are summarized in Appendix A.

2.4.2 Isobaric Energy Recovery Devices

The most efficient ERDs available on the market are those that employ the positive displacement principle. Many isobaric devices enable simple, variable adaption of discharge volume and hence recovery (Harris, 1999; MacHarg and Pique, 2002a) and possess a high device efficiency of approximately 98% (Geisler et al., 1997). Examples of positive displacement devices include ERI's PX (MacHarg 2001; Wang et al., 2005b; Stover, 2007), Flowserve/Calder's DWEER (Shumway, 1999; Andrews and Laker, 2001), Siemag's Pressure Exchange System (PES) (Geisler et al., 1999, 2001), and the Aqualyng system (Drablos, 2001). Because of higher efficiency, these devices are considered to be the most promising and competitive technologies on the market (Wang et al., 2005a).

There are currently seven different isobaric ERDs available, including

- Flowserve/Calder's DWEER
- Aqualyng's Recuperator
- KSB's SalTec
- Energy Recovery Inc.'s PX
- Spectra Watermakers's Clark Ppump and Pearson Pump
- Danfoss's iSave.

The differences between the seven devices lie predominantly in the design of equipment used to achieve pressure exchange and the control of the devices. Although all of the devices utilize positive displacement, all except for the PX use a multichamber piston-type arrangement to achieve energy exchange. The DWEER, SalTec, and Recuperator all operate with two or more chambers and valving mechanisms to change the sequencing (direction of travel) of the ERD. All of these systems can be used, assuming adequate capacity, over a range of recoveries. The nature of the isobaric ERD requires a booster pump to offset pressure losses that are due to piping, membranes, and the ERD before cycling water back into the system. The iSave has this pump built into the device.

In 2005, it was reported that the two largest SWRO desalination plants with DWEER devices were the Ashkelon plant in Israel and the Tuas plant in Singapore, with capacities of 100 million m^3/y (Kronenberg, 2004; Kiang et al,. 2005) and 30 mgd (Industry News, 2004), respectively. A number of early adopting plants, dating back to the 1980s, are located throughout the Caribbean and Europe. Andrews and Shumway (1999) detailed DWEER installations at different locations in the Caribbean Islands with capacities ranging from 3200 to 10,300 m^3/d and train sizes ranging from 1600 to 2500 m^3/d. Reductions in SEC were also reported at an ERD upgraded SWRO plant in Grand Cayman, Spain. The SWRO plant had an SEC of 3.00 kWh/m^3 prior to installation of a DWEER system, which reduced the SEC to 2.22 kWh/m^3 (Andrews et al., 2001).

Independent literature indicates that DWEER installations are reported to have extremely high efficiencies of about 95% (Oklejas, 2003; Kiang et al., 2005; Schneider, 2005; Wang et al., 2005a) Flowserve/Calder recently reported that the efficiencies can be as high as 98%. DWEER allows an almost constant efficiency over a wide range of changing conditions, especially considering the full range of operating pressure conditions typical in the RO industry (Schneider, 2005; Verbeek, 2005). Although DWEER is reported to have a design life in excess of 25 years, the valving has historically been subject to wear and failure. The development of the LiNX valve is credited with greatly improving the performance of the units. Also, because of the sequencing, it has been reported that pulsations and "water hammer" pressure surges have complicated or delayed the startup of new plants (*Membrane Technology News Bulletin,* July 2010).

The Aqualyng Process (Drablos, 2001) uses the saline reject in a sequential process to directly pressurize feed seawater. Although limited reports are available on the operation and performance of the Recuperator, Aqualyng has included it in several sizeable desalination plants. One recent example is a 50,000-m^3/d SWRO facility located in the Caofeidian Industrial Zone, 220 km east of Beijing, China (*Water and Desalination News,* March 2010).

Drablos (2002) also reported on the performance of Aqualyng Pressure Recuperation in SWRO plants in Gran Canaria, Spain.

In a pressure-exchanger device, high-pressure concentrate flows through the unit and transfers energy directly to a portion of the incoming lower-pressure seawater feed (Stover, 2004). The heart of the device is a single cylindrical ceramic rotor that facilitates pressure exchanges. Ceramic was selected as the ideal material for this application because it is tough, corrosion-proof, and dimensionally stable. The rotor contains axial ducts arranged in a circle around a center tension rod (*Membrane Technology News Bulletin,* 2004). The rotor spins within a ceramic sleeve and is enclosed on either end with dedicated feed and concentrate ceramic end covers. The bearing and sealing surfaces are the ceramic parts themselves, and bearing lubrication is provided by high-pressure feed water. The concentrate end cover contains a high-pressure concentrate port for incoming concentrate (HP IN) and a low-pressure concentrate port for outgoing concentrate (LP OUT). The feed water end cover likewise contains two feed water ports (LP IN and HP OUT). The pressure-exchanger system allows the feed and concentrate streams to come into direct contact, and minimal mixing of the streams occurs within the duct. Mixing increases the feed water TDS, requiring slightly higher feed pressures to maintain the desired flux and recovery (Stover, 2004).

ERI's marketing literature reports that the PX is the most energy-efficient commercially available ERD, with a flat performance curve and reported efficiencies of over 95% (Andrews et al., 2001; MacHarg and Pique, 2002a; Oklejas, 2003; Wang et al., 2005a, 2010; Stover, 2007;). However, the analysis typically excludes energy losses in the system caused by the backpressure required to minimize cavitation and the lower efficiencies of the booster pump. Noise from the device also often exceeds recommended Occupational Safety and Health Administration (OSHA) standards, requiring installation of noise enclosures or separate ERD rooms in the facility. The compact system can handle high flow capacity and unsteady conditions (Stover, 2007; Mambrettia et al., 2009). In addition, the control and instrumentation of the PX is more comprehensive than for most other ERDs, even though the device has only a single moving part with minimal required preventative maintenance.

MacHarg (2007) compared the performance of various ERDs at low to medium capacity; the results are summarized in Figure 2.8. At very low capacities, where highly efficient piston pumps can be applied, very low SEC can be achieved using pressure-exchanger technology (approaching 2.1 kWh/m^3). Otherwise, low- to medium-capacity systems typically possess higher SEC than higher-capacity systems, as a result of lower centrifugal pump efficiencies at low capacity. Several recent products have been targeted specifically toward these markets, including the iSave, Clark Pump, Pearson Pump, and APP ERD.

Specializing in small-capacity desalination systems, Spectra Watermakers has developed systems based on the Clark Pump and the Pearson Pump. The Clark Pump is single-vessel, two-chamber, isobaric ERD. Similar to larger isobaric, multichamber ERDs, an external pilot valve (reversing valve) controls the sequencing and flow of water through the device. The system is designed for fixed recovery, depending on the area displaced by the shaft on the concentrate side of the piston. Systems based on the Clark Pump are available in capacities ranging from 144 to 1,000 gpd.

The Pearson Pump is a positive-displacement, three-cylinder, reciprocating HPP with the same motors and crankcases used in conventional RO system feed pumps. The Pearson Pump head delivers water to the membranes in the same way as conventional feed pumps, but is capable of recovering the energy in the concentrate. This is done by returning the concentrate

to the Pearson pump at high pressure, where it flows into the pump cylinders on the undersides of the pistons, transferring its energy to the feed water. The energy recovered from the concentrate reduces the load on the pump motor, thereby reducing energy consumption. Like other similar devices (such as Vari-RO), the Pearson Pump operates at a fixed recovery. The device is available in multiple designs ranging from 20% to 50% recovery with permeate production between 55 and 220 gal/h.

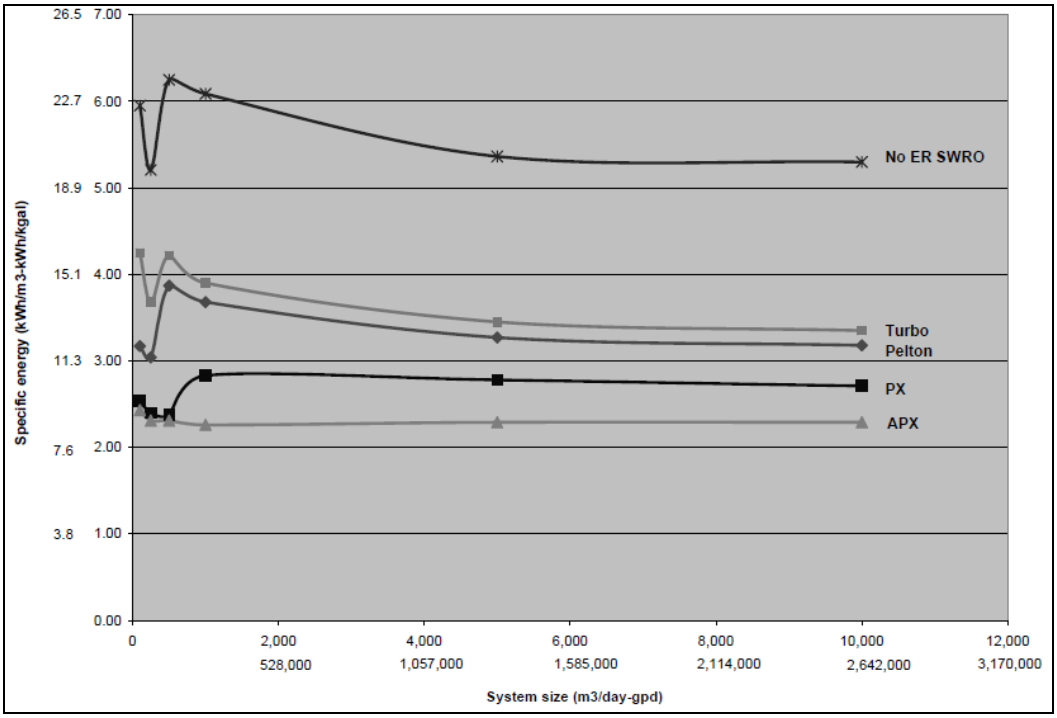

Figure 2.8. Typical SEC for energy recovery devices at low capacity (MacHarg, 2007).

Although Clark and Pearson pumps improve energy efficiency for very small applications, mid-size applications tend to possess lower efficiencies. Development of the APP–APM (axial piston motor) and iSave ERDs is anticipated to provide greater efficiencies in this flow range.

Danfoss, a company specializing in desalination and other HPP applications, has released the iSave, an isobaric ERD with integrated booster pump. The iSave consists of a pressure exchanger, a high-pressure positive displacement booster pump, and an electric motor, coupled into a single package, reducing footprint. The manufacturer claims that the technology used in the pressure exchanger is based on technology used in the Danfoss APPs, and the booster pump is based on the vane pump principle, enabling a very light and compact design. The iSave is a self-lubricating stainless steel device, duplex or super-duplex depending on the application. The vane pumps are fixed displacement pumps in which the flow is proportional to the number of revolutions of the driving shaft enabling flow control. The electric motor provides speed control of both the pressure exchanger and the high-pressure booster pump on the same shaft, preventing overspin and overflushing. A variable-frequency drive (VFD) controlling the speed of the iSave also provides fail-safe communication to the service staff. Current applications for the iSave device include marine and container-based installations. Few independent publications detailing performance of the iSave exist. Although the manufacturer claims up to 94% efficiency, the basis of this claim is

unknown. If this figure includes the booster pump component, the iSave may be one of the most efficient ERDs available on the market. The iSave is targeted toward seawater desalination systems up to 4000 m^3/d capacity.

MacHarg (2007), with funding provided by the Office of Naval Research, reported on the development of a new class of axially driven, combination positive-displacement pump ERDs. In a patent awarded in 2010, MacHarg describes the invention as "a pumping machine, that can serve a system as the sole main pump for pressurizing a primary liquid flow, incorporates, in a single machine, a rotor-drum type APP and a pressure exchanger that recovers energy from a secondary liquid flow such as the brine discharge from an RO seawater desalination system, with benefits including fewer moving parts and small machine size along with lower capital and operating costs. A single rotor-drum containing the cylinders and pistons is located between two end blocks, one or both configured with manifold passageways, ports and sliding valves. A swash-plate at one end reciprocates the pistons axially when the rotor-drum is rotated. Two working chambers, primary and secondary, are formed at opposite ends of a single piston in each cylinder, thus enabling the single rotor-drum to function as a primary liquid-pressurizing axial pump with sliding valves at the primary end enabling primary liquid pumping, and as a secondary outflow-driven pressure exchanger PX recovering energy from pressure drop in the secondary liquid flow and thus contributing work to primary pumping, saving energy and reducing operating costs."

It is reported from field data that the APP-APM technology can successfully reduce the power consumption in mid-size SWRO systems to as low as 2.1 kWh/m^3 (MacHarg, 2007). Currently, full-scale production of this pump has not begun, but working prototypes have been developed.

2.5 Energy Recovery Devices and Process Configurations Selected for Model

2.5.1 Energy Recovery Devices

Many attempts have been made to compare and recommend the most appropriate devices for energy recovery (Mandil et al., 1998; Harris, 1999). The main objective of this evaluation is to use all the information collected from the literature review and present a comparative discussion of each of the ERD technologies relative to their applicability and effectiveness. Each of the ERDs discussed in Section 2.4 was evaluated on the basis of performance reported in the engineering literature, results of manufacturer or vendor studies, and the industry's experience with the ERD. Specifically, the ERD technologies were compared with respect to their reliability, flexibility, adaptability, potential for modifications, and other related relevant factors. These evaluation criteria are summarized in Table 2.4.

Based on the evaluation, the following ERDs were selected to be incorporated into the tool:

1. Turbochargers
   a. FEDCO HPB
   b. ERI Low Pressure Turbocharger (LPT), High Pressure Turbocharger (HALO), and Hydraulic Turbocharger (HTC)
2. Flowserve/Calder Pelton Wheels
3. Isobaric devices
   a. ERI PX

b. Flowserve/Calder DWEER

These ERDs were selected for incorporation into the tool based on their use in the vast majority of new RO installations because of their high efficiency, superior performance, and track record in the marketplace. The design and operational characteristics of the selected devices are summarized in Appendix A.

Table 2.4. Multicriterion Comparison of ERD Technologies

Type	Scale	Capacity (m^3/d)	Recovery (%)	Mixing[a] (%)	Lubrication[b] (%)	Noise (dB)	Booster Pump	Efficiency (%)	Concentrate Backpressure (bar) min	Concentrate Backpressure (bar) max
PX	Commercial	109 to 1,640*	Variable	3.1% at 50% Recovery	1% of HPP Flow	>87 dB	Required	94 to 98%	1 bar	
DWEER	Commercial	2400 to 8,450*	Variable	< 2.5%	1% of HPP Flow	<80 dB	Required	Up to 98%	1 bar	
SalTec	Commercial		Variable			<80 dB	Required		1 bar	
Pelton Wheel	Commercial	360 to 24,000	Minimal variation	None	None	>87 dB	None	Up to 90%	0	Free discharge
Turbocharger–FEDCO	Commercial	360 to 84,000	Minimal variation	None	None	>87 dB	None	65 to 85%	1 bar	
Turbocharger–ERI	Commercial	136 to 65,500	Minimal variation	None	None	>87 dB	None	50 to 80%	1 bar	
HPB–Hemi	Commercial		Minimal variation	None	None	>87 dB	None			
iSave	Commercial	504 to 960	Variable			>87 dB	None	Up to 93%[c]	1 bar	
Clark Pump	Commercial		Fixed			<80 dB	None			
Pearson Pump	Commercial		Fixed			<80 dB	None			
APP–HP	Developing		Fixed*			<80 dB	None			
RWE	Developing					<80 dB	Required			
Aqualyng	Commercial		Variable			<80 dB	None			
FS–ERD	Developing					<80 dB	None			
HER	Developing		Fixed			<80 dB	None			
VariRO	Developing		Fixed			<80 dB	None			
RO Kinetic	Developing					<80 dB	Required			

*Note that the DWEER and ERI devices are easily operated in parallel for larger capacities.
[a]Mixing.
[b]Lubrication.
[c]Device + booster pump.

2.5.2 Process Configurations

Many RO + ERD process configurations are available. Parameters that influence the configuration are as follows:

1. *Source Water.* The type of source water has a tremendous influence on the design of the RO system, and thus how the ERD is implemented. For example, SWRO systems are typically single-stage, and the ERD is used to pressurize the feed. With brackish water systems, the ERD is typically used to boost the pressure of the second or third stage.
2. *Number of ERDs.* A system may incorporate one ERD per RO train or a common energy center (for seawater systems).

2.5.2.1 Seawater Desalination

ERDs are widely used on SWRO systems. Because of the high osmotic pressure inherent in seawater, the required feed pressures are high, typically 800 to 1000 psig, and recoveries are low (typically less than 50%). Therefore, most SWRO systems consist of a single stage. Recoveries beyond 50% are unusual because of the feed pressure limitations of the RO element (1000 psig) relative to the required feed pressure necessary to overcome the osmotic pressure at more than 50% recovery. Thus, the RO concentrate has a significant embodied energy content, as much as 60% of the energy input to the feed when recovery is low (around 35%). Thus, there is ample opportunity to recover the energy in the concentrate with an ERD. Turbochargers, Pelton Wheels, and isobaric devices have all been used successfully in SWRO systems.

The process configurations shown in Figures 2.9, 2.10, and 2.11 are typical for seawater.

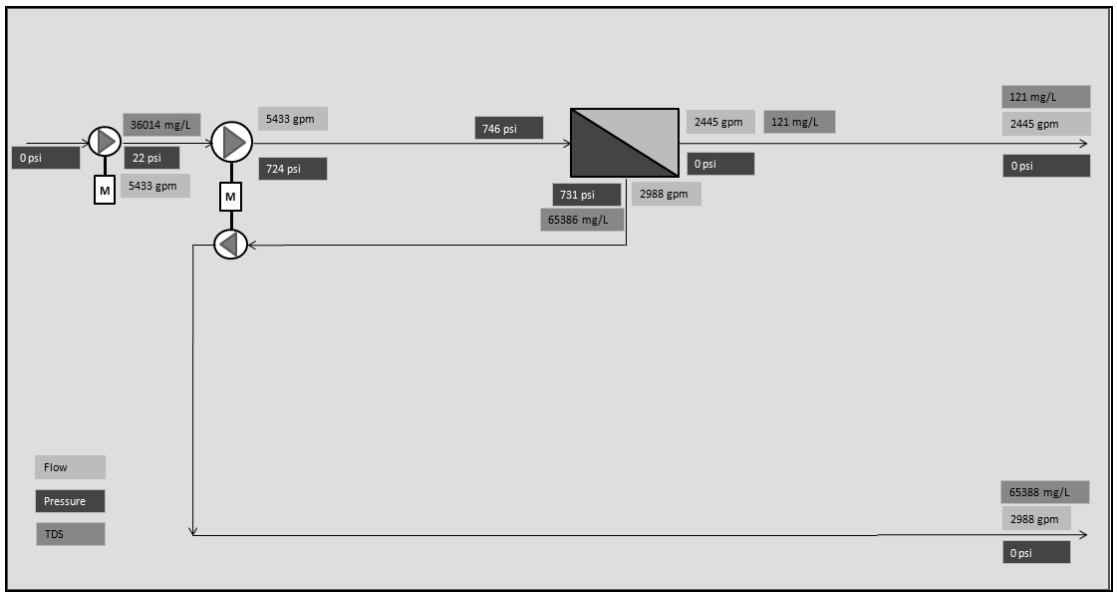

Figure 2.9. SWRO train with Pelton Wheel.

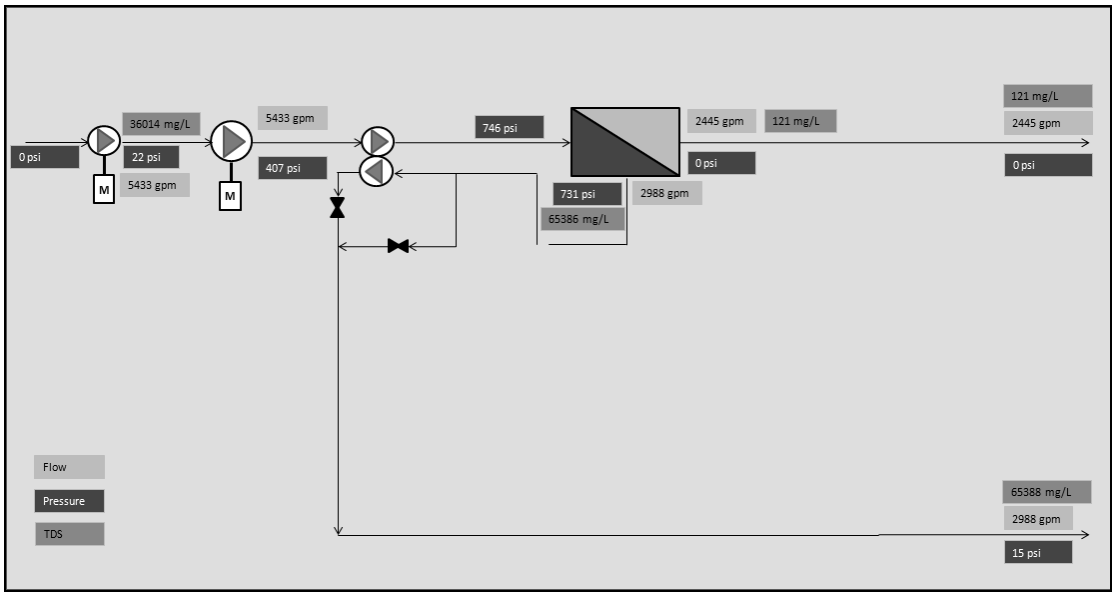

Figure 2.10. SWRO train with turbocharger.

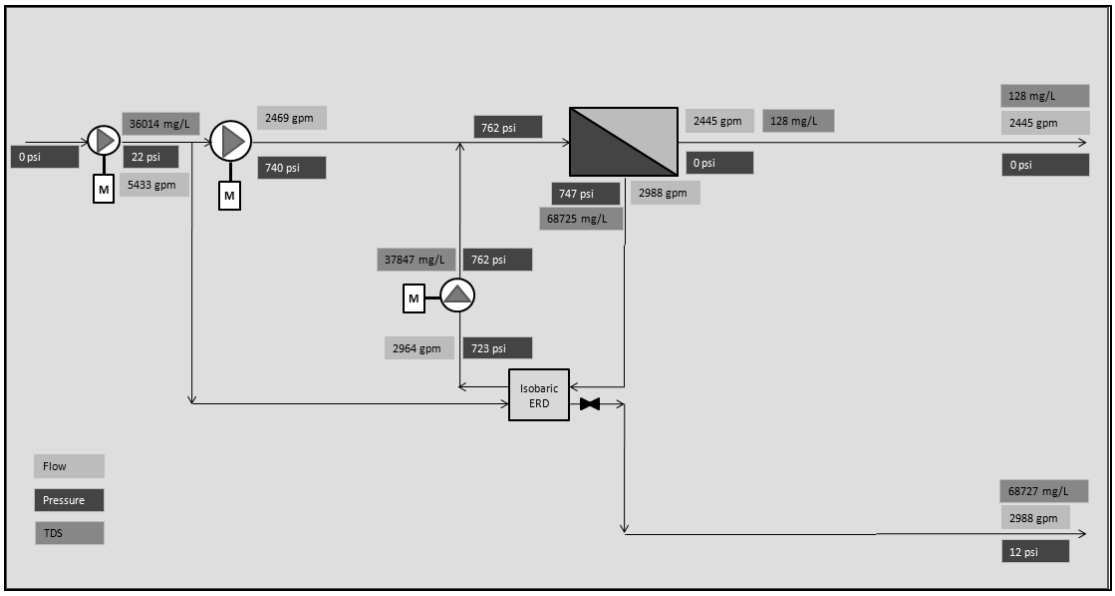

Figure 2.11. SWRO train with isobaric ERD.

2.5.2.2 Brackish Water and Wastewater RO

Because of lower salinity, and thus osmotic pressure, as well as the higher membrane/water transfer rate, brackish and wastewater RO systems are typically multistage and have recoveries in the 75 to 90% range. Pelton Wheels are usually not incorporated into these lower-pressure RO systems, although some early brackish plants did use Pelton Wheels (for example, the Yuma Desalting Plant in Arizona). For these multistage systems, the ERDs can be utilized to boost the feed, similarly to how they are used in single-stage systems; however, they are more commonly used to boost a subsequent stage to provide a better flux balance between stages.

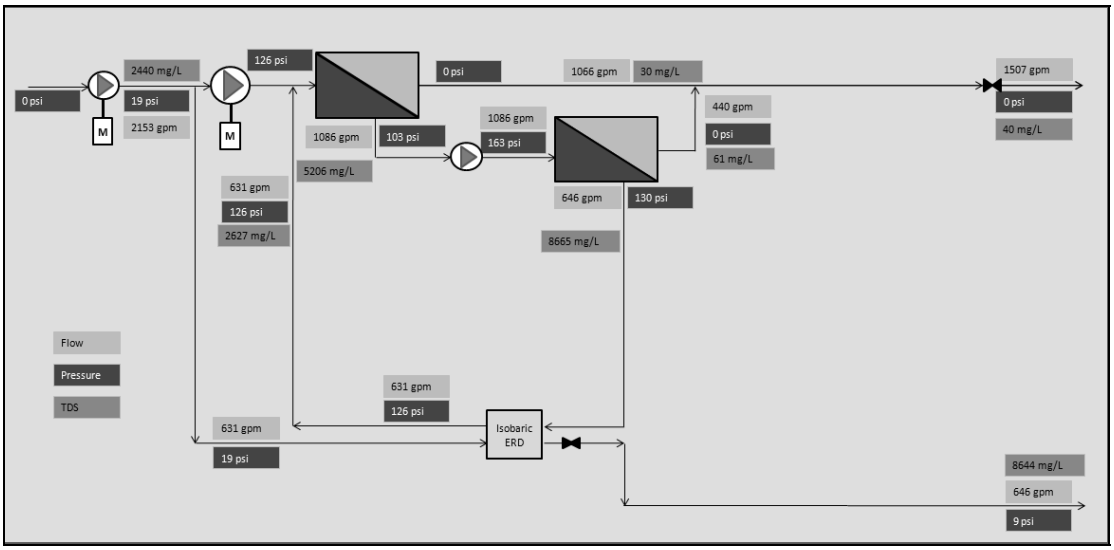

Figure 2.12. Two-stage BWRO with isobaric ERD boosting the feed.

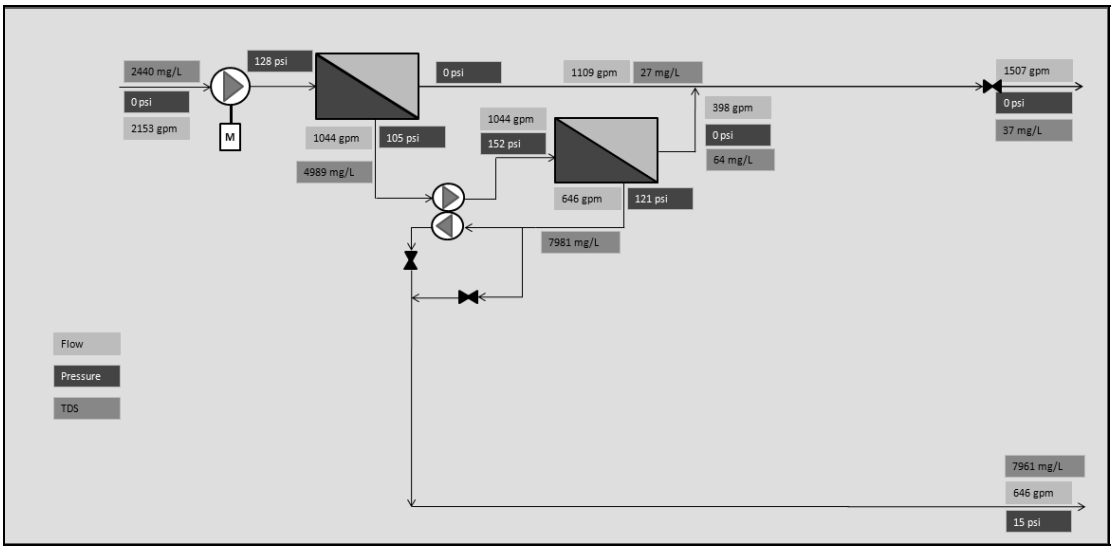

Figure 2.13. Two-stage BWRO with turbocharger.

Figure 2.12 presents an example of a multistage brackish RO with an isobaric ERD boosting the feed water.

Instead, the ERD can be used to boost a subsequent stage, as shown in Figures 2.13 and 2.14. Turbochargers incorporated into multistage RO systems are typically used to boost a subsequent stage, as the turbocharger efficiency is highly dependent on the ratio of the flow of concentrate water to the flow of the water boosted, termed the reject ratio. This is discussed in detail in Chapter 3.

For a three-stage RO system, the ERD can boost the feed, the second stage, or the third stage. With the turbocharger, the choice of whether to boost the second or third stage will be heavily influenced by the reject ratio.

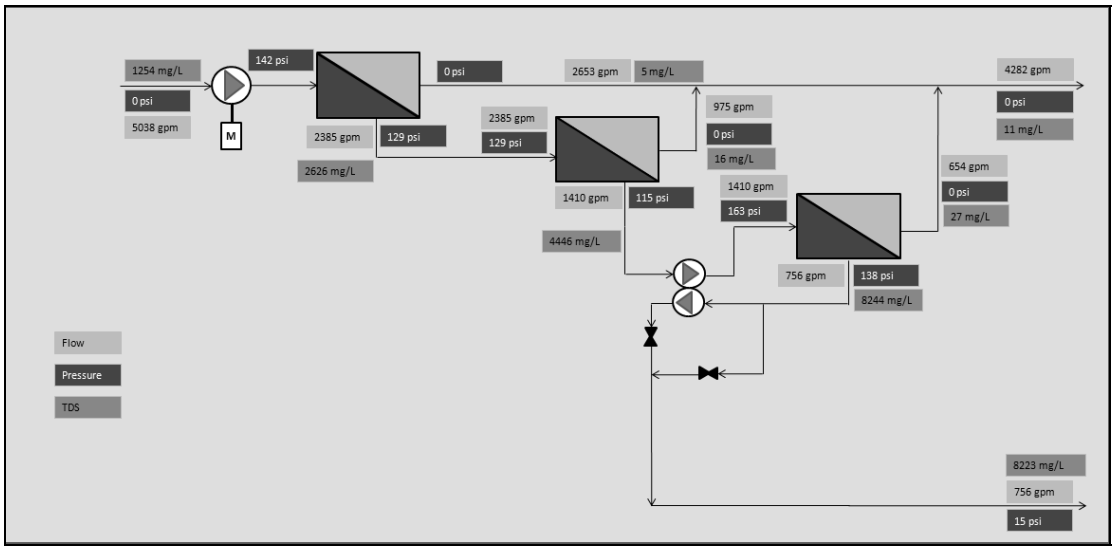

Figure 2.14. Three-stage BWRO with turbocharger boosting the third stage.

2.5.2.3 Standard Configuration Options (SWRO, BWRO, and Wastewater RO)

Feed Pressure Control. The feed pressure to the RO process varies based on a number of factors, including feed water temperature and salinity variations, as well as the water permeation rate of the RO elements that are due to aging, scaling, and fouling. To account for these factors, the pumping system is designed so that feed pressure can be varied in order to maintain a constant permeate flow rate. The configurations shown in Figures 2.9 through 2.14 incorporate a VFD on the high-pressure RO feed pump for pressure control. This is typical for medium and large BWRO and wastewater systems, as well as smaller SWRO systems, as this is the most energy-efficient method of feed pressure control, despite the fact that VFDs possess parasitic energy losses of approximately 1% to 2%. For medium- and large-capacity SWRO systems, VFDs have high capital costs, and design engineers will typically use a VFD on the smaller (motor) RO supply pump (upstream of the cartridge filter) to provide the necessary feed pressure range while reducing capital cost as well as increasing the efficiency of the HPP. Smaller RO systems may eliminate the VFD altogether and replace it with a throttling valve, either on the feed line between the high-pressure RO feed pump and the membranes or on the common permeate line leaving the RO train. Regardless of where the throttling valve is placed, this is not an energy-efficient method of pressure control, as the valve wastes energy that is not recovered by the ERD.

Stage Permeate Flow Control. In a multistage BWRO or wastewater RO system, the permeate flow in one or more stages is often controlled to prevent upstream stages from having substantially higher flux (permeate flow/membrane area) than downstream stages; this is termed "flux balancing." A stage with a substantially higher permeate flux would be susceptible to rapid membrane fouling. Stage permeate flow can be influenced in a number of ways. Prior to the adoption of ERDs, flux balance was achieved by placing backpressure on the first stage and sometimes the second stage (in a three-stage system) using a throttling valve in the stage permeate line. This approach increases system energy consumption by requiring higher feed pressures to the train. The permeate backpressure approach using standard pressure vessels is limited. The standard permeate port design for 8-in. pressure vessels has a typical maximum design pressure of 125 psi. A second approach is to install a booster pump between stages to increase driving pressure to downstream stages. This is more energy-efficient because it matches driving force pressure to the feed salinity of each stage without wasting energy across a throttled valve. When energy recovery is incorporated into the RO design, flux balancing can be achieved in several ways. With a two-stage system, flux balancing is provided by the ERD's pressure boost in Stage 2 using a turbocharger (see Figure 2.13).

As shown in the stage permeate flow examples in Figures 2.15 and 2.16, energy recovery can be combined with both permeate throttling and boost pumping. The three-stage RO system at the Luggage Point Advanced Water Treatment Plant in Brisbane, Australia uses the approach shown in Figure 2.15.

The options described here for feed-pressure control and stage permeate flow control are incorporated into the tool.

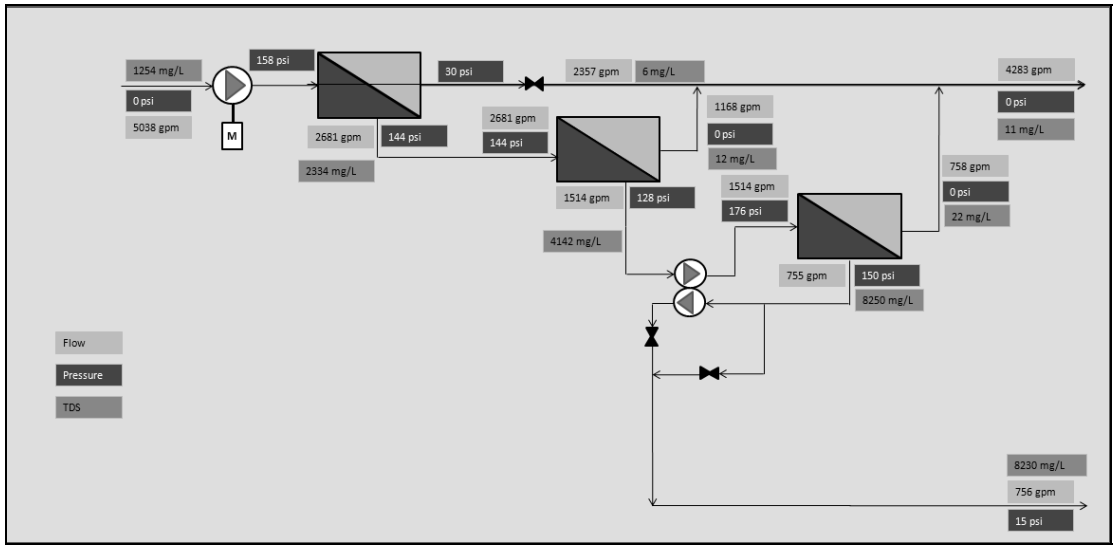

Figure 2.15. Three-stage BWRO with turbocharger boosting the third stage and a permeate backpressure valve on the first stage.

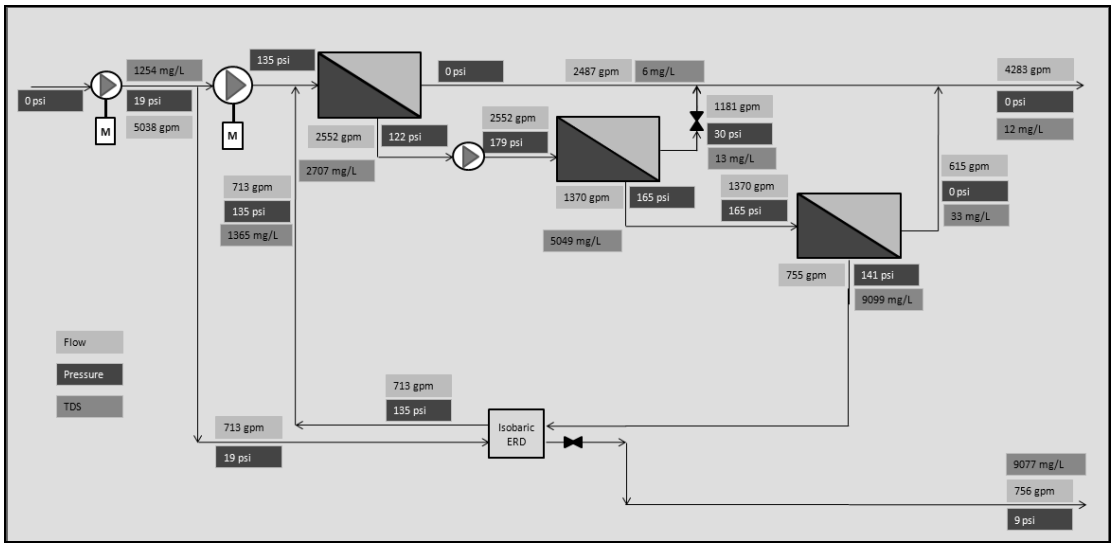

Figure 2.16. Three-stage BWRO with isobaric ERD boosting the feed and a permeate backpressure valve on the second stage.

2.5.2.4 The Pressure or Energy Center

The majority of RO installations that utilize energy recovery incorporate the ERD on a per RO train basis where the concentrate from a single RO train is processed through a dedicated ERD, where the pressure-boosted feed or interstage flow is within the same RO train. In contrast, some larger SWRO plants employ the "pressure center" (or energy center) concept, where the concentrate from multiple trains is combined and sent to a pressure center that contains multiple ERDs operating in parallel. The pressure-boosted feed stream exiting the ERDs is then conveyed to a common header that feeds water to multiple RO trains.

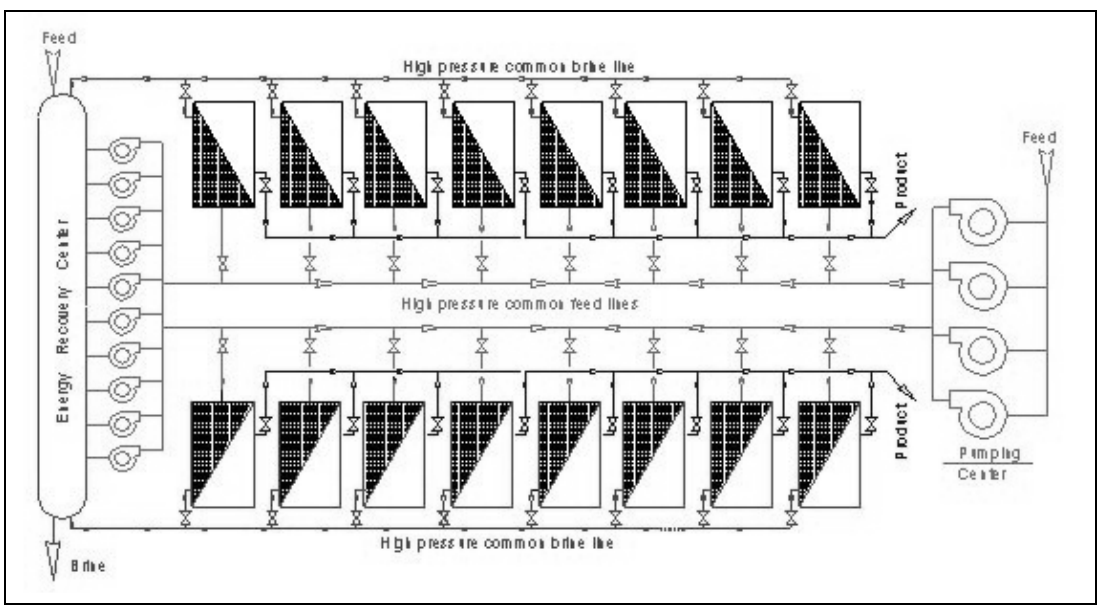

Figure 2.17. Pressure center schematic for Ashkelon Desalination Plant (IDE Technologies Website, www.IDE-tech.com).

Faigon and Liberman (2003) report on the use of centralized pumping systems to increase energy efficiency in a desalination plant. The authors discuss the use of centralized high-pressure pumping and centralized energy recovery. When fewer, larger HPPs are used, the pumps can operate at higher specific speeds with higher efficiencies. The Ashkelon Desalination Plant in Israel, which utilizes four 33% HPPs (in a 3 + 1 arrangement), reports HPP efficiency of approximately 90%. The pressure center schematic for the Ashkelon plant is provided in Figure 2.17.

However, the pressure center design introduces some process limitations. First, the systems are reported to take a comparatively longer time and more permeate flush water to start up and shut down. In addition, when such centralized systems are utilized, balancing the performance of different membrane trains is important to manage fouling. Two different design concepts are reported in the literature. The first utilizes feed-throttling valves on the inlet of each membrane train to control the membrane flux. In the second design, the flux of the individual trains is controlled using permeate backpressure. In either case, energy losses are incurred with the pressure center approach to balance intertrain fluxes. This energy loss can be on the order of ~3% of the total RO energy consumption.Chapter 3.

Chapter 3

Tool Development

3.1 Development of a Reverse Osmosis Model

A review by the authors of the current desalination literature and tools indicates that no existing model available on the market is capable of conducting RO projections, comparative energy calculations, and providing cost estimates. This tool provides these capabilities, providing new information to evaluate various ERDs for implementation into municipal brackish-water, treated wastewater, and seawater desalination applications.

This chapter describes the tool concept and key components.

3.1.1 Reverse Osmosis Theory[1]

In natural osmosis, a semipermeable membrane separates pure water (solvent) from a salt solution (solute). Pure water naturally passes through the membrane to dilute the salt solution; the driving force for the flow is the difference in chemical potential between the two liquids. Chemical potential is directly proportional to changes in temperature and pressure and inversely proportional to changes in solute concentration. Water flow continues until the pressure created by the hydraulic head equals the osmotic pressure of the salt solution. At this point, the two liquids are said to be in osmotic equilibrium. This process is illustrated in Figure 3.1a.

In RO, applying external pressure to the salt solution allows the net natural flow of water to be reversed, as illustrated in Figure 3.1b.

In any membrane process, flow characteristics are unique functions of the membrane polymer. For example, product flow or solute (salt) passage for a polyamide polymer is different from that for a cellulose acetate polymer, which is different from that for a polysulfone polymer. If the membrane area in a device is twice that of another device using the same polymer, the water flow will be double. Similarly, a thicker membrane will allow less water flow than a thinner membrane of the same polymer. Some factors, such as the membrane material, membrane area in a device, and membrane thickness, are set and controlled only by the membrane manufacturers and system suppliers. Other factors, including the pressure applied in the system and the concentration differential across the membrane, can be adjusted by the end user.The high feed pressure requirements associated with RO make it an ideal environment for the use of ERDs and systems.

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[1] Taken from American Water Works Association (1998).

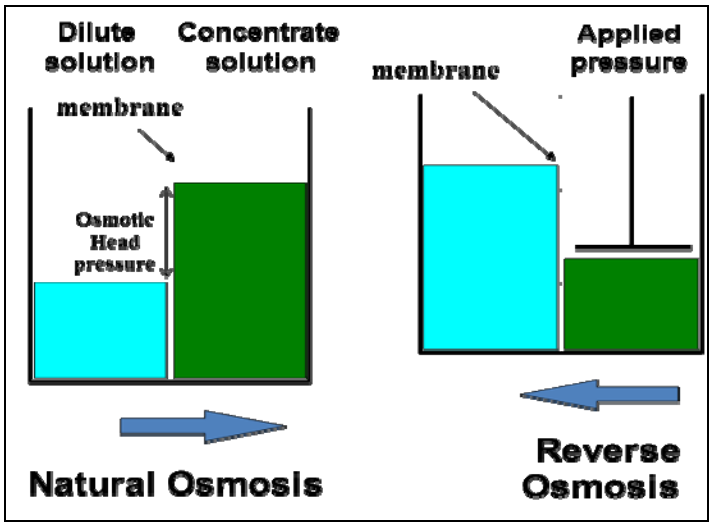

Figure 3.1. Natural osmotic flow and reverse osmosis.

3.1.2 Design Equations

This section describes the fundamentals associated with diffusion-controlled membrane processes, such as RO. In these processes, water is forced through a membrane by a pressure differential (a type of motion called convection), and dissolved salts pass through the membrane because of a concentration differential (a type of motion called diffusion). Because the membrane is semipermeable, both dissolved salts and water are transported to differing degrees through the molecular structure of the active surface layer of the membrane.

The standard model for describing the RO process is the homogenous solution diffusion (HSD) model, which illustrates the effects of feed concentration, membrane characteristics, recovery, and pressure on permeate concentration. The HSD model incorporates operational parameters such as water quality, water recovery, and membrane-specific coefficients to determine system performance. The HSD model does not consider the effects of certain chemical and physical constraints, and it makes certain simplifying assumptions.

Figure 3.2 shows a single membrane element, as well as the terminology typically used to describe flow and concentration. The following equations are commonly used for RO and NF membrane processes to determine system efficiency.

Mass balance for water flow:

$$Q_f = Q_p + Q_c, \tag{3.1}$$

where Q_f = feed water flow rate, Q_p = permeate flow rate, and Q_c = concentrate flow rate.

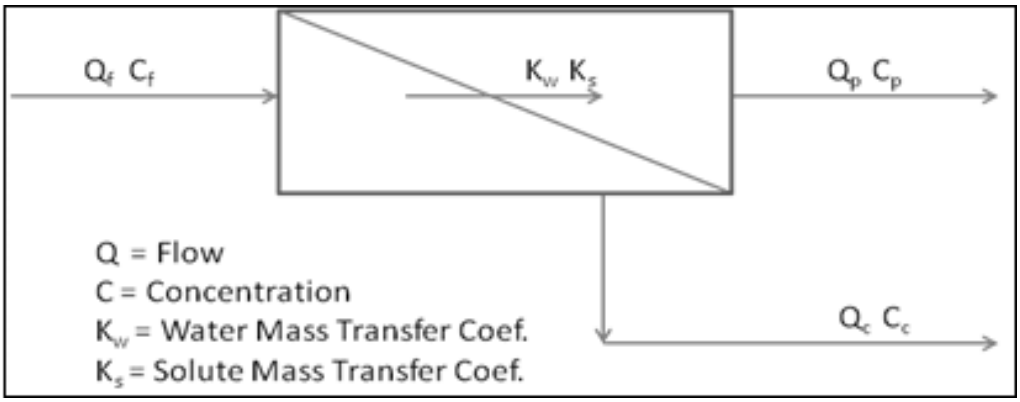

Figure 3.2. Schematic diagram of a reverse osmosis membrane element.

Mass balance for solute flux:

$$Q_f C_f = Q_p C_p + Q_c C_c, \tag{3.2}$$

where C_f = feed water solute concentration, C_p = permeate solute concentration, and C_c = concentrate solute concentration.

Product recovery rate:

$$REC = \frac{Q_p}{Q_f} \tag{3.3}$$

where REC = decimal fraction of product water recovered from feed water.

Further equations for calculating the water and salt flux through the membrane, osmotic pressure, mass transfer coefficients, and permeate concentration are included in AWWA (1998).

3.1.3. Calculation Methodology

This section describes the calculation methodology for the RO projection portion of the tool. The calculations are used to determine the physical parameters of the RO projection, including pressures, fluxes, and water quality.

3.1.3.1 General Comments

The tool flow is designed as shown in Figure 3.3.

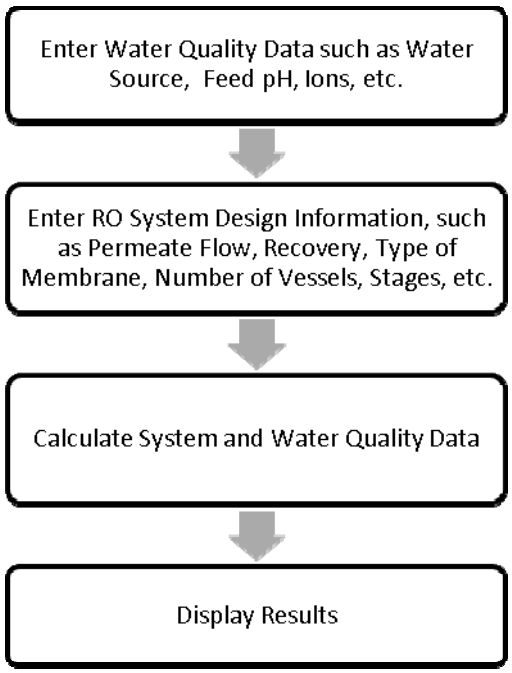

Figure 3.3. General program (tool) flow.

The data and calculations are organized by type and function onto different "sheets" or tabs on the spreadsheet. Buttons on the sheets provide an alternate means of navigation between sections.

3.1.3.2 Reverse Osmosis System Calculation Methods[2]

The general approach used in the tool is the same as that used by most commercial membrane design programs, including IMSDesign by Hydranautics and ROSA by Dow Water and Process Solutions. Essentially, the user enters a system design and feed water quality, and the program executes detailed calculations.

With a reasonable design, convergence is usually quite rapid. The tool makes one simplification over most commercial programs that greatly increases the calculation rates: each vessel is converted to the form of one element, which directly returns the performance for each stage in the system. With this simplification, the output file does not calculate information (e.g., flux, recovery) by element. Rather, the tool calculates salt flux on an ion-by-ion basis during each pass through the system and balances carbonates in the concentrate and permeate analyses while accounting for the free passage of carbon dioxide (CO_2) through the membranes.

[2] The calculation methodology in the tool is similar to that used in the Total Flux and Scalant Program (TFSP) by Tom Wolfe of Perlorica Inc., February 2000.

Water flux, or more properly the flow rate, is calculated according to

$$Q = AValue * A * \left[P_f - \frac{dP}{2} - (\pi_m - \pi_p) \right], \tag{3.4}$$

where Avalue = membrane water permeability coefficient, A = membrane area, P_f = membrane feed pressure, dP = membrane differential pressure (Feed – Brine), π_m = osmotic pressure, membrane, and π_p = osmotic pressure, permeate.

The concentration of each ion in the permeate is calculated as follows. A variable, MembDiffCalc, is first defined for each ion. MembDiffCalc is the effective difference in concentration of the ion from the membrane surface to the permeate,

$$MembDiffCa\,lc = C_{avg} * CP - C_p, \tag{3.5}$$

where C_{avg} = average concentration of the ion, CP = concentration polarization, and C_p = permeate concentration of ion,

$$C_p = MembDiffCalc * \left[\frac{BValue * BCorrectionByIon}{Pnet * AValue + BValue} \right], \tag{3.6}$$

where Bvalue = membrane salt (ion) permeability coefficient, BcorrectionByIon = correction factor for the ion, and Pnet = net driving pressure.

Pnet is the feed pressure less one-half the differential pressure less the osmotic pressure difference between the average feed stream and the permeate. “BcorrectionByIon” is an ion-specific constant stored in the spreadsheet. This is the ratio of salt flux for the ion in question to either chloride or sodium.

Because the permeate concentration has some effect on the water flux and required pressure, an iterative approach is necessary to solve the system. The general steps are as follows:

1. Acquire a valid feed water analysis and target feed pH from the user-supplied data. Enter these values into the internal variables.
2. Acquire flow and recovery information from the graphic screen.
3. Acquire from the user the suggested array, stage, and vessel layout and save in the internal variables. Typically, a system with higher recovery needs more stages. For example, a 75% recovery system might specify six elements per vessel, two stages total in the array, and an array layout of 16:8—that is, 16 first-stage vessels feeding 8 vessels in Stage 2.
4. Acquire from the user the selected membrane element information. When the user selects the type of element, the program loads the specific data about the element, such as A value, B value, B value relative to sodium (Na) or chloride (Cl) for each ion (dependent on membrane type), area in square meters (m^2), and differential pressure coefficients.

5. Set up the selected membrane element in the vessel and calculate delta pressure and concentration polarization coefficients (called the "BetaCoef" in the code) for the selected elements:

$$CP = EXP\ (BetaCoef * REC), \tag{3.7}$$

where BetaCoef = concentration polarization coefficient and REC = recovery.

6. At this point, calculations are ready to begin. The first step is to guess the applied pressure needed to produce the water flow rate required. To do this, the total membrane area in the system and the feed osmotic pressure are calculated. Based on nominal recovery and nominal rejection for the element, a concentrate concentration is estimated by mass balance. The concentrate osmotic pressure is then calculated. Next, a differential pressure is calculated for the first and last elements in the system and the average is used to guess a differential pressure for the system. The "guess" pressure needed is then calculated:

$$\text{Guess} = \frac{Q}{\text{AValue} * A} + \text{Total dP} + \frac{\pi_f + \pi_p}{2}, \tag{3.8}$$

where A = total membrane area in the system, TotaldP = total differential pressure, π_f = feed osmotic pressure, and π_p = permeate osmotic pressure.

7. Guess the net pressure, which includes osmotic pressure and differential pressure losses, so that the applied pressure is increased by the average of the feed and concentrate osmotic pressures and the differential pressure. Osmotic pressure is calculated and summed for each ion in the analysis. TOC contributions (if any) are ignored in the osmotic pressure estimation because the contribution is highly dependent on the type of organic carbon present:

$$\pi = RT * \sum_{all\ ions} \alpha_i [c]_i, \tag{3.9}$$

where R = universal gas constant, T = temperature, α_i = activity coefficient, and c_i = concentration ($[c_i]$ = molar concentration).

8. The calculations are arranged in a do-while loop that starts with an assumed applied pressure. From this pressure, flow rates and concentrations are calculated on a vessel-by-vessel basis through the system. The total calculated flow is then compared to the user-provided target permeate flow. If the result is low, then the pressure is raised proportionally; if high, then the pressure is lowered proportionally. Once the calculated flow is within 0.05% of the target flow, the calculation program terminates and data are returned to the spreadsheet for display to the user.

9. If convergence cannot be obtained, the user is alerted. Failure to converge usually occurs when too few or too many vessels are specified for the flow rates that are required. The applied pressure required to produce the needed flow cannot be reconciled with the differential pressures necessary to pass the flow through the system in such a case.

3.1.3.3 Differential Pressure

The TFSP equation for differential pressure was based on feed brine flow but does not account for membrane feed spacer thickness differences. The TFSP equation is

$$dP = dPCoef * \left[\frac{(Q_f + Q_c)}{2} \right]^{1.5} . \tag{3.10}$$

For higher accuracy, the tool uses Equation 3.10, but varies the differential pressure coefficient depending on the feed spacer thickness.

3.1.3.4 Carbonate Equilibrium and pH

The calculation of the appropriate carbonate and pH distribution is an important part of this program. Note that membrane systems readily pass CO_2, whereas bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) ions are quite well rejected. Thus, the permeate side of the membrane is enriched with CO_2, whereas the feed/concentrate side of the membrane is enriched with CO_3^{-2} and HCO_3^-. The net effect of this separation is to lower the pH of the permeate while raising the concentrate pH. The tool effectively models this behavior.

The steps necessary to calculate the CO_3 equilibrium are as follows:

1. The solution ionic strength is calculated, defined as:

$$IS = 0.5 * \sum_{all\ ions} [c_i] * z_i , \tag{3.11}$$

   where z_i = ionic charge, and pK1 and pK2 are corrected for the solution temperature.

2. Ionic strength corrections are then applied to pK1 and pK2. The methods are described in Stumm and Morgan (1996).

3. pK1 and pK2 are converted back to K1 and K2 values.

4. The hydronium ion [H+] concentration is calculated from solution pH.

5. The mole fraction (fraction of the total inorganic carbon) for HCO_3^- is calculated from K1, K2, and the pH. If the HCO_3- concentration was specified, then the total carbon is calculated from the mole fraction of HCO_3^-. If total carbon was specified, then the HCO_3^- concentration is calculated using the mole fraction of HCO_3:$^-$

$$MHCO_3 = \left(\frac{(H^+)}{K1} + 1 + \frac{K2}{H^+} \right)^{-1} , \tag{3.12}$$

$$TC = \frac{[HCO_3]}{MHCO_3} , \tag{3.13}$$

where $MHCO_3^{--}$= mole fraction of HCO_3^- and ^-TC = total carbon.

6. Knowing the total carbon, the CO_2 and CO_3^{-2} values are then calculated from the pH and from K1 and K2, as shown in Equations 3.14 and 3.15. The values are in moles per liter:

$$[CO_3] = TC * \left(\frac{(H^+)^2}{K1 * K2} + 1 + \frac{H^+}{K2} \right)^{-1} \tag{3.14}$$

$$[CO_2] = TC * \left(\frac{(K1)^2}{H^+} + 1 + \frac{K1 * K2}{(H^+)^2} \right)^{-1} \tag{3.15}$$

7. Once the carbonate equilibrium is determined, the pH for the permeate and concentrate streams is then calculated using

$$pH = \log\left[0.82 * \frac{HCO_3}{CO_2} \right] + 6.3 \tag{3.16}$$

3.1.4 ERD Calculation Sequences

If the application includes an ERD, additional calculations are necessary, depending on the device selected.

3.1.4.1 Turbocharger

A turbocharger is an integral turbine-driven centrifugal pump that transfers hydraulic energy from the RO concentrate to the RO feed stream. The energy transfer results in a feed pressure increase. Figure 3.4 presents a PFD of a single-stage RO unit with a turbocharger boosting the feed. Note that the high-pressure RO feed pump effluent passes through the turbocharger, resulting in a pressure boost. The turbocharger has no effect on the amount of flow that passes through the high-pressure feed pump; however, the pressure required from the high-pressure RO feed pump is lowered by the boost pressure of the turbocharger.

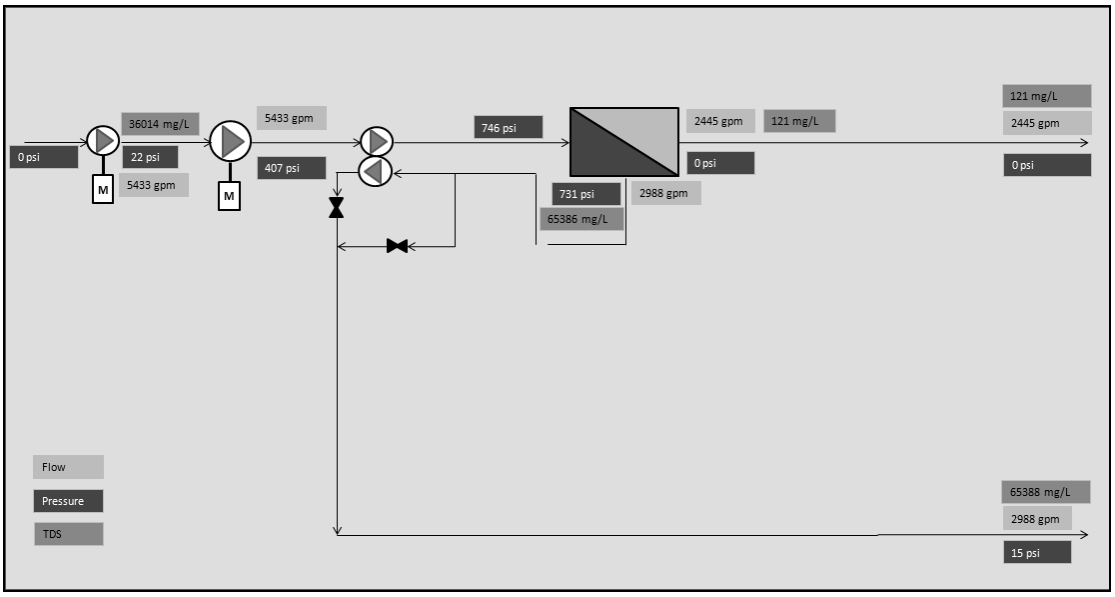

Figure 3.4. Single-stage RO system with hydraulic turbocharger.

The turbocharger boost pressure can be calculated using the equation

$$\text{Boost Pressure} = \text{nte} \cdot \text{Rr} \cdot (\text{Pbr} - \text{Pe}), \tag{3.17}$$

where nte = net transfer efficiency of the turbocharger, Rr = ratio of the RO concentrate flow to the RO feed flow, Pbr = brine pressure at the turbocharger inlet, and Pe = brine pressure at the turbocharger exit.

Through the transfer of energy from the concentrate to the feed, the pressure that must be developed by the HPP is decreased and the pump power requirement is likewise decreased. The amount of power or energy saved through energy recovery by the turbocharger can be calculated as follows:

$$\text{Energy Savings} = \text{Boost Pressure} \cdot \text{Boostflow} \cdot c, \tag{3.18}$$

where c = conversion factor, equal to 0.000436 if the units of flow and pressure are gpm, and Boostflow = flow rate boosted by the turbocharger.

In addition to boosting the feed pressure to an RO system, as shown in Figure 3.4, a turbocharger can also be used to provide an interstage boost in a multistage BWRO system array, as shown in Figure 3.5.

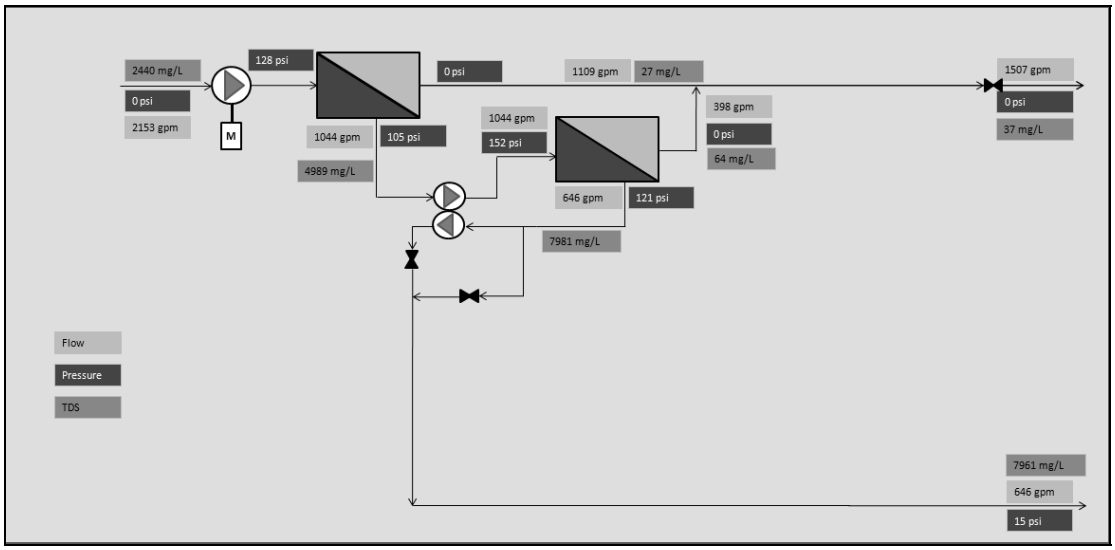

Figure 3.5. Two-stage RO system with turbocharger boosting pressure to second stage.

The transfer efficiency of the turbocharger is a function of the device itself, the feed flow rate boosted, and what is termed the reject ratio. The flow dependence is rather small as long as it is within the design criteria of the device, and it is specific to the turbocharger design. Per Figure 3.6, however, the impact that the reject ratio has on the efficiency is substantial. The efficiencies are highest when the reject ratio is between 60% and 75% and fall off sharply at values below 50%. The reject ratio is the high-pressure concentrate flow into the turbocharger divided by the low-pressure flow that is boosted by the device.

Analysis of the two-stage turbocharger system depicted in Figure 3.5 demonstrates why multistage RO systems typically boost the interstage feed and not the feed to the entire system. In the example shown in Figure 3.5, the reject ratio for the interstage boost is equal to 260 gpm divided by 521 gpm, or 50%. If the feed to the RO was boosted, the reject ratio would be 260 gpm divided by 1,302 gpm, or 20%, resulting in a drastically lower turbocharger transfer efficiency.

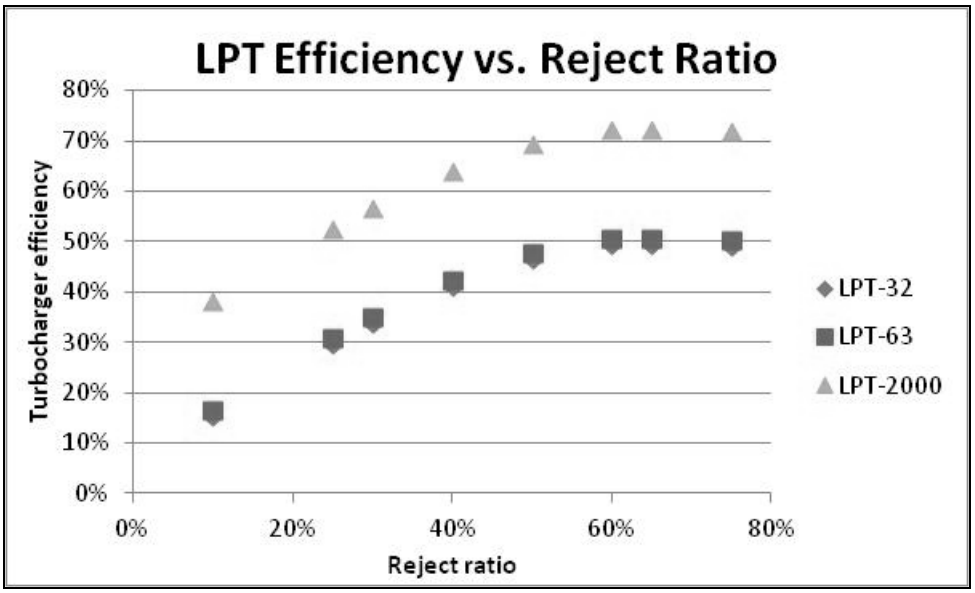

Figure 3.6. Turbocharger dependence on reject ratio.

The efficiency dependence on reject ratio is defined as follows:

if 60% < RR < 70%, if RR < 60%, nte(RR) = nte(Device) – abs(RR - 0.6)$^{1.55}$;

if RR >70%, nte(RR) = nte(Device) – abs (RR - 0.7)^{2},

where RR = reject ratio = concentrate flow divided by boosted flow, and nte = device-rated net transfer efficiency.

3.1.4.2 Isobaric ERD

Isobaric ERDs can be grouped into pressure exchangers and work exchangers, but the principles are similar. The high-pressure RO brine is passed to the ERD, where the pressure energy is transferred to a portion of the feed. This feed stream is then directed to a small booster pump that is sized to boost the pressure back to that required for the membrane feed. As a result, the flow requirement on the high-pressure RO feed pump is dramatically reduced. With the isobaric ERDs, the high-pressure RO feed pump capacity is similar to that of the RO permeate flow, not the full feed flow, as in all other applications.

A single-stage RO system equipped with an isobaric ERD is illustrated in Figure 3.7.

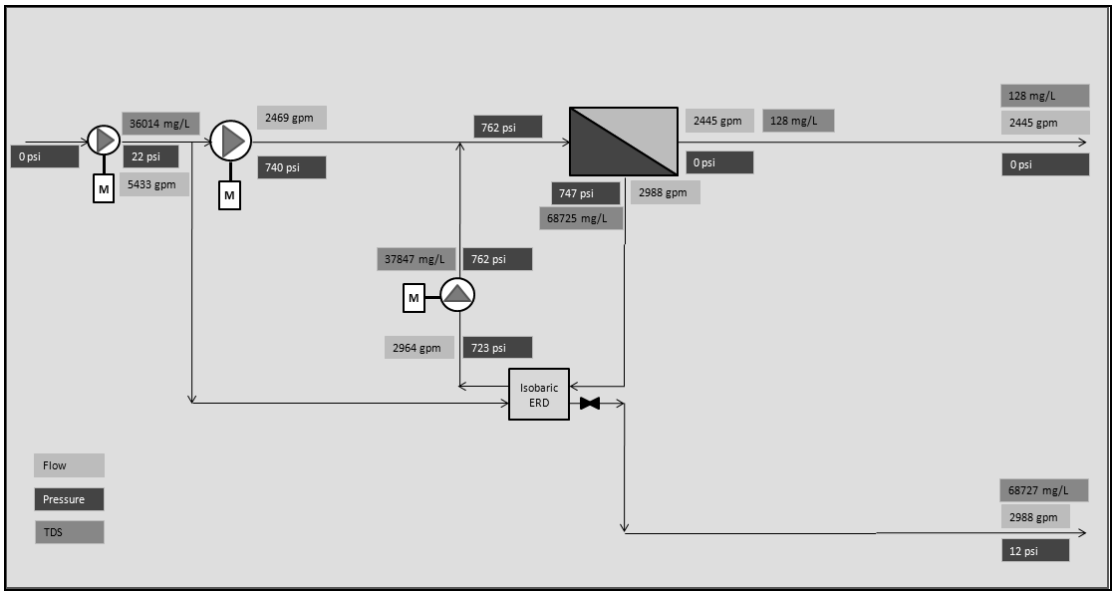

Figure 3.7. Single-stage RO system with isobaric ERD.

Because of the nature of the operation of the isobaric ERDs, a small amount of flow is transferred from the RO brine side of the device to the seawater stream. This flow is called lubrication flow or leakage and results in a small loss of efficiency. The amount of lubrication flow is a function of numerous variables, including pressure, temperature, and system flow, and can be estimated by the equation

$$\text{Lubrication Flow} = \%\text{Leakage} \cdot (\text{HPP Flow}), \tag{3.19}$$

where HPP Flow = flow rate of the high-pressure RO feed pump and %Leakage = 1%.

Isobaric ERD operation adds to the salinity of the membrane feed water though the previously defined leakage. This salinity increase or "mixing" varies with the membrane recovery rate as follows:

$$\text{Salinity Increase} = \text{REC} \cdot \text{MIX} \cdot 1.04, \tag{3.20}$$

where REC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow, and MIX = volumetric mixing constant for the ERD.

The net result of the lubrication flow and the salinity increase is a decrease in the amount of energy that the isobaric device can recover. Lubrication represents a decrease in the amount of flow that the ERD passes to the membrane feed, and the salinity increase associated with the isobaric ERD results in an increase in the required net driving pressure of the membrane operation.

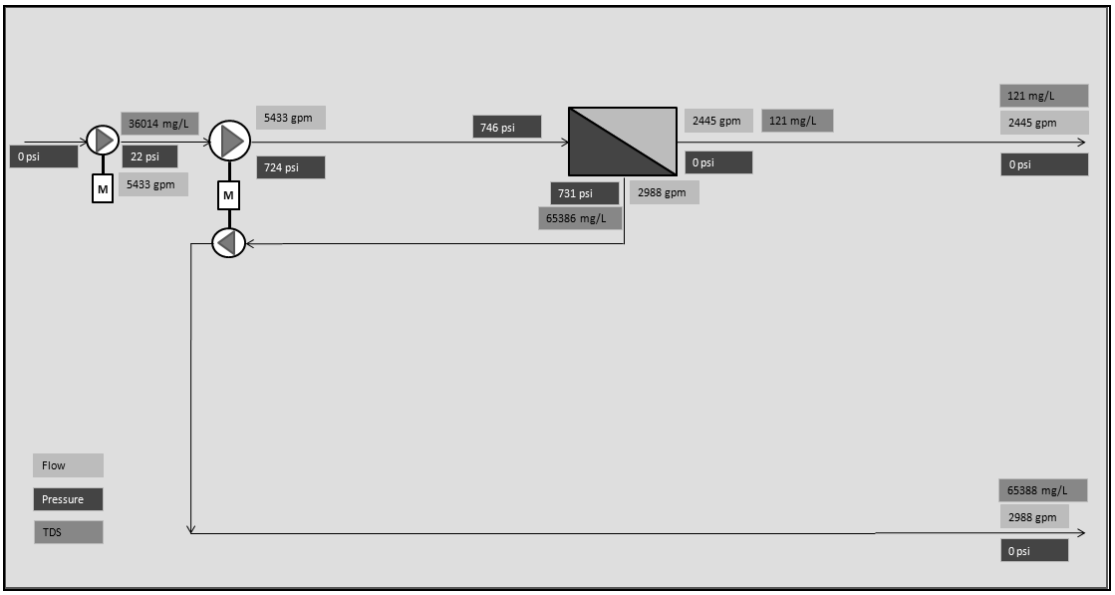

Figure 3.8. RO system with Pelton Wheel.

Per Figure 3.7, an RO system with an isobaric ERD will require a booster pump. Therefore, the energy use of such a system will involve the energy requirements of the high-pressure RO feed pump and the booster pump. Each can be calculated as shown in the following equations. Note that the power equations in this section are normalized to the permeate flow of the system and are expressed in kWh/1,000 gal permeate. To calculate straight kW, the total is multiplied by 1,000/24:

$$\text{HPP kWh/1,000 gal permeate} = c \cdot [(1 + \%\text{Leakage}) \cdot \text{HPP P}) / \text{HPP eff} / \text{HPP motor eff}], \quad (3.21)$$

where c =conversion factor, equal to 0.007248 if pressure units are in psi; HPP P = pressure increase of the high-pressure RO feed pump; HPP eff = high-pressure RO feed pump efficiency; and HPP motor eff = high-pressure RO feed pump efficiency.

$$\text{Booster kWh/1,000 gal permeate} = c \cdot [(1 - \%\text{Leakage}) \cdot (1 - \text{REC}) / \text{REC} \cdot (\text{HPP dP} + \text{Mem d}P + \text{Pipe dP}) / \text{Booster Pumpeff} / \text{Booster motor eff}] \quad (3.22)$$

where c = conversion factor, equal to 0.007248 if pressure units are in psi; REC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow; HPP dP = pressure increase of the high-pressure RO feed pump; Mem dP = membrane pressure drop (feed – brine); Pipe dP = ERD piping pressure drop; HPP eff = high-pressure RO feed pump efficiency; and HPP motor eff = high-pressure RO feed pump efficiency.

3.1.4.3 Pelton Wheel or Impulse Turbine

The Pelton Wheel converts pressure energy in the RO concentrate into kinetic energy of a rotating wheel. This rotating power output is used to assist the main rotor in driving the RO HPP. Pelton Wheels are usually directly coupled to the pump/motor arrangement, as shown in Figure 3.8.

Energy consumption for the high-pressure RO feed pump/Pelton Wheel combination is calculated using the following equations:

HPP kWh/1,000 gal permeate = c · HPP dP/REC/HPP eff/HPP motor eff, (Eq. 3.23).

where c = conversion factor, equal to 0.007248 if pressure units are in psi; HPP dP = pressure increase of the high-pressure RO feed pump REC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow; HPP eff = high-pressure RO feed pump efficiency; and HPP motor eff = high-pressure RO feed pump efficiency.

PWER kWh/1,000 gal permeate = c · (Pbr – Pe) · (1-REC) / REC · nte, (Eq. 3.24).

where PWER kW = energy recovered by the Pelton Wheel; c = conversion factor; Pbr = brine pressure at Pelton Wheel; inletPe = brine pressure at Pelton Wheel; exitREC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow; and nte = net transfer efficiency of the Pelton Wheel.

3.1.5 Projection Model Validation

The tool developed by CH2M HILL is essentially an RO projection software program incorporating ERDs. The tool allows the user to select RO membranes from different RO manufacturers and ERDs from various ERD manufacturers and provides both an energy analysis and a rough capital cost estimate of the RO system. To CH2M HILL's knowledge, no other tool offers this information.

Validation of the model consists of

1. Executing a set of RO projections on software provided by RO manufacturers to determine that the RO membrane performance is accurately portrayed by the tool.
2. Running a set of analyses from the ERD manufacturer software to establish the accuracy of the ERD effect on energy cost.
3. Refining the capital cost estimates. The cost results were discussed with the individual ERD vendors to confirm accuracy.

3.2 Cost Modeling

The decision to use an ERD for a particular RO application is typically based on economics: Will the initial capital cost associated with the installation of the ERD equipment be captured by the savings in operational energy in a reasonable period of time? If the answer is yes, then the question becomes: Which ERD will achieve the lowest cost of water produced for the application?

The tool is designed to answer these questions. An Association for the Advancement of Cost Engineering (AACE) Class IV Capital Cost estimate is generated for the RO mechanical equipment and additional ERD equipment required. The tool also calculates a net present value (NPV) estimate of the operational ERD savings over the life of the RO mechanical equipment. The average annual operational savings, the total net present cost of the ERD, and the payback period are then presented to the user.

3.2.1 Cost Model Structure

The costs are based on the AACE standards. Class IV (+50%/-30%) estimates are generally prepared based on limited information. They have a fairly wide accuracy range and are used for project screening, determination of feasibility, concept evaluation, and preliminary budget approval. They represent pricing for designs that are between 1% and 15% complete. At the time of the estimate, designs typically comprise a minimum of the following: plant capacity, block schematics, indicated layout, PFDs for main process systems, and preliminary engineered process and utility equipment lists.

The cost estimates in the model are in 2011 dollars. To keep the tool valid for the future, the user can select the construction start date and an inflation rate. This is used to escalate the construction and O&M costs to the appropriate year.

3.2.2 Reverse Osmosis Configurations

The tool executes a model of the following four major RO configurations:

1. RO equipped with a turbocharger-type ERD
2. RO equipped with an isobaric-type ERD
3. RO equipped with a Pelton Wheel-type ERD
4. RO with no ERD

There are many subconfigurations: the use of a VFD on the feed pump, the use of an interstage booster pump, the possibility of having permeate backpressure on one or more stages of the RO system, etc. Each of these can be used with one of the four major RO configurations. All four configurations are possible for high-salinity SWRO applications within the tool. Configurations 1, 2, and 4 are options for lower-pressure brackish systems. It is not economically feasible to add a Pelton Wheel to a low-pressure RO system.

3.2.3 Capital Cost Model

3.2.3.1 Direct Costs

Direct cost inputs to the cost portion of the model include the RO mechanical equipment and the ERD-related equipment. Direct costs thus include the RO high-pressure feed pump and VFD or discharge throttling valve, RO pressure vessels and support rack assembly, RO membranes, interconnecting piping, valves, and instrumentation. The ERD-related equipment includes not only the ERD itself, but any interconnecting piping, valves, and instrumentation required for its operation and control.

Ancillary equipment required for the RO system that is not related to the ERD is not included in this cost model. The goal of the tool is not to calculate the overall cost of making water, but rather to determine if an ERD makes economic sense and, if so, which ERD makes the most economic sense. This is performed by determining the capital cost and energy cost differences between systems with and without an ERD.

The membrane element costs and ERD-related costs were generated using a combination of ERD vendor quotations and previous quotations that CH2M HILL has accumulated for ERD-related equipment. These costs conform to AACE Class II (+20%/-15%) standards, whereas

all other costs represent Class IV estimates. The RO mechanical equipment cost consists of the piping, valves, and pumps included in the specified system. The piping and valve costs are estimated by generating a typical layout for the user-selected scenario and measuring the amount of piping needed. The pump costs are estimated using a dollars per horsepower ($/hp) equation developed by CH2M HILL. Installation costs were included for all direct costs in this model.

The four major RO configurations have differences in equipment and system operation. Those differences in relation to the capital cost model are as follows:

- *Turbocharger.* An RO system using a turbocharger will include the cost of the turbocharger itself, piping to and from the turbocharger, and some valves and instrumentation. In addition, a turbocharger is essentially a pressure-boosting device. Because the turbocharger increases the net driving pressure of the RO system by boosting the pressure of the feed or interstage flow, it reduces the pressure that must be developed by the HPP and thereby reduces its power input. Thus, introduction of a turbocharger into a new system results in a capital cost decrease associated with the lower horsepower (size) of the HPP. The tool includes this cost savings in its analysis of the capital costs related to the turbocharger ERD.
- *Isobaric ERD.* As with the turbocharger, inclusion of an isobaric ERD in the RO system will result in additional costs for the ERD, piping valves, instrumentation, etc. However, with an isobaric ERD, the net effect on the HPP is a substantial decrease in flow, not pressure. Regardless, the size of the high-pressure feed pump and motor are reduced, and again, there is an associated cost savings or offset for a new system. Isobaric ERDs require an additional booster pump in the system to add a small amount of pressure to the ERD effluent stream in order to reintroduce this water to the membrane feed.
- *Pelton Wheel.* The Pelton Wheel is directly connected to the pump motor. Interconnecting piping and a very small amount of additional equipment is required. The Pelton Wheel, like the turbocharger and the isobaric ERDs, provides a reduction in the high-pressure feed pump costs. With the Pelton Wheel ERD, this cost savings is offset by the requirement for a smaller HPP motor.

3.2.3.2 Indirect Costs

The user has the ability to add indirect costs to the cost model. The “Cost Summary” page has user-input boxes for a mechanical allowance, electrical allowance, profit, engineering, and contingencies. These indirect costs are applied to the final process mechanical installed cost to generate a total capital cost.

3.2.4 Operating Cost Models

Operating cost inputs in the model include power consumption of the RO system and membrane replacement cost. Each of these is an ongoing cost over the expected life of the equipment. In order for the tool to compare these ongoing costs to the initial capital cost of the ERD-related equipment and generate a payback period, the operating costs are calculated by a present-worth factor. The present worth normalizes annual operating costs over a fixed time period to a present worth amount.

3.2.4.1 Energy Consumption

The tool uses complex algorithms to determine the net driving pressure required for the RO system based on feed water salinity, water temperature, recovery, membrane, etc. The net driving pressure will depend on the configuration of the system and may include inputs from the high-pressure RO feed pump, interstage booster pump (if applicable), ERD booster pump, etc. The user can use the tool to determine the differences in energy consumption and capital investment between a RO system designed with and without an ERD.

A NPV calculation is used to find the total investment needed in today's dollars to pay the future power costs for the duration of the plant. This calculation utilizes user inputs for inflation rate, discount rate, and plant duration, as well as the calculated annual power cost. A sample NPV calculation is as follows:

$$NPV\ (\$)\ \sum_{n=1}^{\text{Duration}} \frac{\text{Annual Power Cost}*(1+\text{Inflation Rate})^{n}}{(1+\text{Discount Rate})^{n}}$$

(Eq. 3.25).

The NPV power cost is then compared with the NPV power cost that would be required if there were no ERD. This provides the total life-cycle cost savings associated with implementing the ERD. Let us hypothetically state that the addition of an isobaric ERD on a 5-mgd (permeate) SWRO train will provide a life-cycle cost savings of $5,000,000 and will require an initial capital investment of $915,000. The tool would determine the payback period as follows:

$$Payback\ period\ (years) = \frac{ERD\ Capital\ Cost\ (\$)}{(\text{NPV(ERD)}-\text{NPV(No ERD)})/\text{Duration}}$$

(Eq. 3.26).

If the life-cycle cost savings is assumed to be consistent throughout the duration of the plant, the annual savings can be calculated by dividing $1,500,000 by the estimated duration of the plant. If the duration is 20 years, this will provide an average annual savings of $250,000. The payback period will be $915,000 divided by $250,000, or 3.66 years.

3.2.4.2 Membrane Replacement

RO membranes are periodically replaced in an RO system. The replacement rate is usually determined by an increase in required net driving pressure (membrane fouling), a degradation in water quality, or a combination of these. Typical membrane replacement intervals vary from 3 to 10 years.

Because RO membrane replacement is done periodically, unlike power use, this is not a relatively continuous cost. Thus, the calculation for the NPV cost of the membrane replacement over the life of the RO equipment differs from that of the power cost. The calculation first determines the number of membrane replacements over the life of the RO equipment, and then calculates the NPV cost of each membrane replacement individually. These individual costs are then summed to determine the NPV cost of the membrane replacement over the life of the equipment:

$$PWMRi = \frac{C_{mem} * (1+I)^{mri}}{(1+D)^{mri}} + \frac{C_{mem} * (1+I)^{mri \times 2}}{(1+D)^{mri \times 2}} + \cdots + \frac{C_{mem} * (1+I)^{mri \times n}}{(1+I)^{mri \times n}} \quad \text{(Eq. 3.27)}$$

where PWMRi = present worth of the membrane replacements over the equipment life, C_{mem} = actual membrane replacement cost expended, I = inflation rate, D = discount rate, mri = membrane replacement interval, n = total number of membrane replacements over the equipment life, and Y = number of years remaining in the last membrane replacement when equipment life is reached.

Note that the membrane cost, and thus membrane replacement cost, does not affect the addition of an ERD to the system. The costs of membrane replacements are calculated and presented in the tool, but they do not change the ERD payback period.

3.2.4.3 Operating Cost Accuracy

The two components of the operating cost are the power cost and the membrane replacement cost, with power cost being the overwhelming contributor. With the tool, power cost is calculated from the RO system's net driving pressure, ERD efficiency, and user inputs for pump efficiency and unit energy cost. Membrane replacement cost is calculated using user inputs for membrane replacement frequency and the future membrane replacement cost.

Appendix A presents two validation examples where membrane feed pressure as calculated using the tool is compared with those calculated using membrane projection software programs from DOW, Toray, and Hydranautics. Membrane feed pressure, which is directly related to net driving pressure, is the primary determinant of the power cost of an RO system. The comparison shows that, on the average, the tool calculates the membrane feed pressure within 7.5% of pressures calculated by the manufacturers' programs.

The tool calculates the energy efficiency of each ERD using algorithms supplied directly from the ERD manufacturers, as shown in Section 3.1. Based on information supplied by these manufacturers, it is assumed that these calculations are within 5% of the actual ERD efficiency.

If the user has accurate power cost information and pump efficiency information, the accuracy of the power cost relies on the feed pressure calculation and the ERD efficiency calculation. This introduces a maximum error of 12.875% into the power cost calculation. However, the tool has the flexibility to bypass the feed pressure calculation and instead let the user input pressure information directly from a projection software program. This reduces the operating cost error from 12.875% to 5%, as the uncertainty associated with the feed pressure calculation is eliminated.

The membrane replacement cost accuracy is based on user inputs and is assumed to be within 5% accuracy, based on the user having access to membrane replacement cost information from one or more manufacturers. Because the membrane replacement cost contributes little to the total operating cost, a lower cost accuracy for this input will have only a minor impact on the total accuracy of the operating cost.

For each scenario evaluated in the tool, the operating cost accuracy is calculated. The tool then combines this with the capital cost accuracy to generate a total present worth cost accuracy.

3.3 Model Tutorial

The tool was created to accommodate a wide variety of SWRO and BWRO system designs. To be able to take advantage of all the tool capabilities, it is important that the user understands how to navigate the graphical user interface. This section provides the user with a walk-through of all the functionalities of the tool.

The tool is protected and will prompt the user to enter a password upon opening. The password is "WRF" (case-sensitive). Each of the sheets within the tool is also protected with the same password.

3.3.1 Graphical User Interface Overview

When the model is opened, a disclaimer window appears that provides the user with general information about the tool. An "About" page is always active in the worksheet that contains more information on the tool, including whom to contact with questions and version information. Navigation through the tool occurs through the "Summary" worksheet, as there is always an option to return to the "Summary" worksheet. Because all other worksheets are hidden, buttons are required to switch from sheet to sheet. Section 3.3.2 summarizes each of the additional worksheets in the model.

The "Summary" worksheet consists of a combination of input cells, output cells, buttons, radio boxes, and check boxes. Any cell with a white background is a user input and must be populated. Any cell with a grey background is a calculated value and cannot be changed.

Buttons are provided on the "Summary" worksheet not only to navigate through the model, but also to provide basic help information. The "User Help" button at the top of the worksheet provides an overview of how to use the tool, whereas the many "Help" buttons on the worksheet describe in more detail how to properly enter the design information. The "English" and "Metric" radio buttons at the top of the "Summary" worksheet enable the user to toggle between these units.

Figure 3.9 provides a screen shot of the tool's "Summary" worksheet.

3.3.2 Model Inputs

This section details how to input the information needed for a complete RO system design. The "Summary" worksheet is split into eight different input boxes. Once the user populates each box with the required information, system projections can be calculated and the PFD can be viewed.

3.3.2.1 Flow Information

Box 1 on the "Summary" worksheet requires user input of permeate flow and recovery. When this information has been entered, the feed flow and flux are calculated. The flux is calculated using the equation

$$Flux\ (gfd) = \frac{Permeate\ Flow\ (gpd)}{Total\ Membrane\ Area\ (sf)} \qquad \text{(Eq. 3.28)}$$

Because flux is a function of permeate flow and total membrane area, the flux will change as the “System Design” and “Membrane Selection” boxes are populated. The typical flux for the water quality selected in the “Water Quality” box is also shown in the “Flow Information” box. Box 1 also allows the user to include bypass flow blended with the permeate flow. Selecting this box requires the user to input the desired permeate TDS, and the program calculates the amount of bypass flow that does not go through the HPP and membrane. Including bypass flow will change the flux of the system because of the decreased feed flow, so an iterative approach may be needed to find the best system design that includes bypass flow.

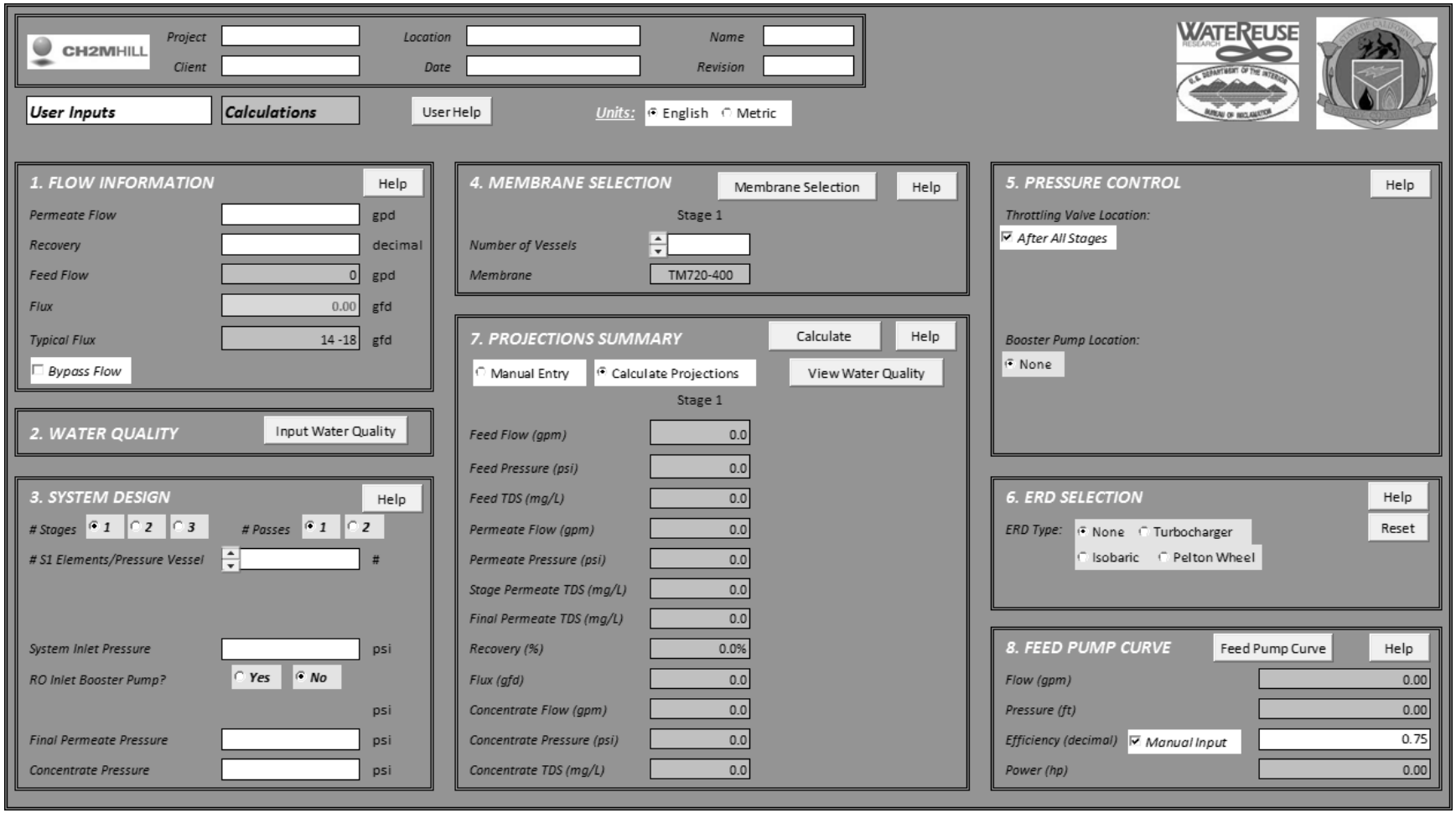

Figure 3.9. "Summary" worksheet.

Table 3.1. Valid Flux Ranges

Water Type	Valid Flux Range (gfd)
RO permeate	18–24
Brackish water from well	14–18
MF/UF pretreated brackish well water	14–18
Conventional pretreated brackish well water	10–14
Seawater from well	8–12
UF/MF pretreated seawater	8–12
Conventionally pretreated seawater	7–10
UF/MF pretreated tertiary waste water	9–14
Conventionally pretreated tertiary wastewater	7–10

3.3.2.2 Water Quality

The user is directed to the Water Quality Worksheet by clicking on the "Input Water Quality" button in the "Water Quality" box. At the top of this worksheet, the user is required to select the source or type of feed water and then enter the feed water temperature and pH. The water type is used to suggest the valid flux range, shown in the "Flow Information" box on the "Summary" worksheet. Valid flux ranges are shown in Table 3.1.

Via radio buttons, the user can then choose to enter only the feed water TDS and have the program use sodium and chloride ions only, or to specify individual ions and enter the concentrations of specific ions. The osmotic pressure, ionic strength, TDS, and ion balance of the feed water are shown at the bottom of the page.

Once a projection has been run, columns E through N will be populated with the appropriate ion concentrations. The "Adjusted RO Feed" column will be different than the "RO Feed" column only for systems that include an isobaric ERD. The difference reflects leakage of high-pressure concentrate into the low-pressure feed through the lubrication function of the ERD. The device salinity leakage is shown on the "Isobaric ERD Selection" page. The "RO Permeate" and "RO Concentrate" columns show the ion concentrations for the overall permeate and concentrate flow streams, respectively, whereas the "Blended RO Permeate" column shows the overall permeate concentrations including any bypass flow. The remaining columns give the permeate and concentrate ion concentrations for each stage in the system. The pH, ion balance, TDS, osmotic pressure, and activity coefficient for each flow stream are shown at the bottom of the page for each of the flow streams.

3.3.2.3 System Design

Box 3 on the "Summary" worksheet contains the "System Design" information. This box has inputs for the user to choose the number of stages and passes in the design and the number of elements per vessel for each of the stages. The tool can accommodate three stages for BWRO systems but only two stages for SWRO systems. The user can choose between one and eight elements per vessel for each stage in the design.

If the user chooses a two-pass system, the program asks the user to enter the desired permeate concentrations for chloride, bromide, and boron. From CH2M HILL's experience, two-pass RO is needed primarily to reduce the concentrations of one or more of these three ions. The tool then estimates the second pass power that would be required for the system based on the feed and desired ion concentrations. CH2M HILL used available membrane projections software to generate a relationship between the desired percent removal of the ions and the second-pass energy consumption. As this additional second-pass RO power requirement does not affect the viability of ERDs, it is not included in the system's overall power consumption.

The "System Design" box also allows the user to enter the system feed, permeate, and concentrate pressures. The "System Inlet Pressure" cell refers to the pressure of the flow stream coming into the RO system. If this pressure needs to be increased prior to the HPP, either for pump suction pressure requirements or to meet the incoming pressure demand of an isobaric ERD, the user can choose to include an RO inlet booster pump and specify the boost pressure. The power required by this pump will then be included in the system power summary.

The "Final Permeate Pressure" cell allows the user to enter the required permeate pressure, excluding permeate backpressure. If the system requires residual permeate pressure, the user should also consider adding a throttling valve "After All Stages" in the "Pressure Control" box. The "Concentrate Pressure" input cell is the pressure of the concentrate flow stream after passing through the ERD or throttling valve. This input is restricted based on the type of ERD that is selected. For example, the Pelton Wheel ERD requires a concentrate pressure of 0 psi, whereas the turbocharger and isobaric devices both require a device-specific minimum concentrate pressure.

The isobaric ERD requires the feed pressure to be at least 10 psi higher than the required minimum concentrate pressure. Thus, if an isobaric ERD is selected, the minimum concentrate pressure will be calculated, and an RO inlet booster pump will be added if needed to increase the feed pressure as required by the device.

3.3.2.4 Membrane Selection

The "Membrane Selection" box allows the user to select the number of vessels per stage. Only the stages specified in the "System Design" box will be visible to enter the number of vessels. The user is advised to follow a vessel ratio of 2:1 for two-stage systems or 4:2:1 for three-stage systems. Unbalanced vessel ratios can result in the system failing to perform accurate projection calculations.

Clicking on the "Membrane Selection" button directs the user to the "Membrane Database" page of the tool, where the user can select the manufacturer and the membrane model. Although it is advised to select the same membrane for all stages in a multistage system, different membranes can be selected for each stage. Clicking on the "View Membrane Database" button shows the user all membranes available for selection.

There are input cells for the membrane age and the percentage annual flux decline. These cells are used to account for membrane fouling. A typical annual flux decline is 5% to 10%. If a new membrane is being evaluated, the user should choose a membrane age of 0 years. Each year of membrane age increases the feed pressure required to meet the permeate flow requirements.

Once a membrane is selected, the tool provides an approximate cost. The user can enter a value in the "User-Override Cost" box if the specific membrane cost is known. The "Application" box will show whether the selected membrane should be applied to a BWRO or SWRO system. The model limits BWRO membranes to feed water with less than 10,000 mg/L TDS and SWRO membranes to feed water with greater than 3,000 mg/L TDS. The model will not calculate projection data if the wrong application is selected.

Clicking the "Add My Own Membrane" box allows the user to add a membrane to the membrane database. If this option is chosen, all fields must be filled in before the user can return to the "Summary" worksheet.

After returning to the "Summary" worksheet, the user should verify that the flux shown in the "Flow Information" box is the desired flux. Once the "Membrane Selection" box has been completed, the flux will not change.

3.3.2.5 Pressure Control

The "Pressure Control" box allows the user to specify if there are throttling valves or booster pumps included in the system design. A throttling valve can be located on either the Stage 1 or Stage 2 permeate piping, or on the common permeate piping for all the stages. If Stage 1 or Stage 2 permeate throttling is selected, the user can enter the throttled pressure in the "Pressure Control" box. If a throttling valve after all stages is selected, the user should enter the final permeate pressure in the "System Design" box.

The user can choose to have an interstage booster pump after Stage 1 and/or after Stage 2. If an interstage booster pump is selected, the user can then specify the amount of pressure boost that each pump will provide to the system. The "Power Summary" page gives the user the option to include VFDs on any of the pumps included in the system, including the high-pressure feed pump. For a multistage isobaric system, the tool will automatically include an interstage boost pump before the second stage and will calculate the amount of pressure required so that an isobaric circulation pump is not needed.

3.3.2.6 ERD Selection

The "ERD Selection" box has radio buttons for the user to select both the manufacturer and the type of ERD included in the system. If "Turbocharger" is selected, the user also needs to specify where the turbocharger will be applied. Selection of the type of ERD is the only input required in this box. After projections have been calculated in the "Projections Summary" box, the "ERD Details" button will be visible in the "ERD Selection" box. Clicking this button will direct the user to an ERD-specific worksheet.

On the "Isobaric ERD Selection" page, the device is sized based on the system flow information and the user-entered manufacturer. Relevant system data is shown on the page, including the total boost pressure provided by the ERD. The "User-Override Cost" box can be used if the user has specific cost information. If the manufacturer is changed, projection data needs to be recalculated in order to view accurate data. For a single-stage system, an isobaric circulation pump is automatically included so that the pressurized feed stream can achieve the Stage 1 required feed pressure. For multistage systems, the tool includes an interstage booster pump instead of a circulation pump.

The only Pelton wheel device available on the "Pelton wheel ERD Selection" page of the tool is from Flowserve/Calder. If a Pelton wheel ERD is selected, then a specific Flowserve model will automatically be chosen and an approximate cost for the device will be shown. The "User-Override Cost" box can be used if the user has specific cost information.

The "Turbocharger ERD Selection" page also shows the specific device that was selected, along with the relevant system data. The "User-Override Cost" box can be used if the user has specific cost information. If the manufacturer is changed, projection data needs to be recalculated in order to view accurate data. The pressure boost provided by the ERD is shown in the box on the lower left of the page.

3.3.2.7 Projections Summary

The tool has the capability to calculate the key outputs (e.g., required feed pressure, feed, permeate and concentrate TDS, and individual ion concentrations) from the RO software portion of the model as a typical projection using the calculations shown in Section 3.1. However, the user can also input projection information from a different software program or from an existing system by checking the "Manual Entry" box in the "Projections Summary" box. In this case, the boxes in the "Projections Summary" box and the ion concentrations on the "Water Quality" page are converted from outputs to inputs, and the user can enter the necessary information. The "Power Summary" and "Cost Summary" pages will then use the input information to complete the respective evaluations.

If the user wants to evaluate multistage systems with manually entered information, the correct interstage boost (either from the interstage turbocharger or from the interstage booster pump in an isobaric application) needs to be entered. Otherwise, the user should use the program's internal calculations to estimate the projection information.

3.3.2.8 Feed Pump Information

The final step for input information is the "Feed Pump Information" box. Once the projection data have been calculated, the high-pressure feed pump flow, pressure, and power are calculated. The user can enter a fixed pump efficiency by checking the "Manual Input" box and entering the efficiency. Pump horsepower is calculated in the tool as

$$Power\ (hp) = \frac{Flow\ (gpm) * Pressure\ (ft)}{Efficiency * 3960} \qquad \text{(Eq. 3.29)}$$

If the user wants to enter data from a specific pump curve to find the pump efficiency and operating speed, he or she should leave the "Manual Input" box unchecked and should click the "Feed Pump Curve" button. This will direct the user to the "Feed Pump Curve" page, where he or she can input flow, pressure, and efficiency data points. The accuracy of the efficiency estimate will increase as more data points are provided. The pump flow and pressure are shown in the "Current Design Points" box. After the pump curve has been entered, the user can click the "Calculate" button to find the estimated speed, efficiency, and power at the design points shown.

This functionality is included in the tool so that users can evaluate the effect that changes in the feed pump design points have on the feed pump efficiency. Because of the high-pressure requirement of RO systems, a small change in feed pump efficiency can result in significant changes in power consumption. This functionality allows the reduced speed pump efficiency

to be included in the power summary, an aspect that is often overlooked in ERD power consumption evaluations. The reduced speed efficiency is calculated using the centrifugal pump affinity laws shown in the equation

$$\frac{N_1}{N_2} = \frac{Q_1}{Q_2} = \sqrt{\frac{H_1}{H_2}} = \sqrt[3]{\frac{P_1}{P_2}} \qquad \text{(Eq. 3.30)}$$

where N = pump speed, Q = pump flow, H = pump pressure, and P = pump power.

3.3.3 Model Outputs

This program performs the system calculations as shown in Section 3.1. The user should be aware that the tool will predict different membrane permeate water quality and net driving pressure requirements than the software programs developed by the membrane manufacturers. The user should refer to the separate software projection programs of the manufacturers to get this information.

The model outputs of this tool include projection information, an overall PFD of the system, a power summary, and a cost summary.

3.3.3.1 Reverse Osmosis Projections Data

If the user clicks the "Calculate" button in the "Projections Summary" box, the tool will calculate projections data using the calculations described in Section 3.1. In some cases, the system will be unable to converge and provide an output. When this happens, a message box will alert the user that the system design must be altered in order to calculate the projections data. If projections are successful, the "Projections Summary" box and the "Water Quality" page will be populated with the projections data. The water quality information can be seen by clicking the "View Water Quality" button.

If the user chooses to manually enter in the projection information, the "Calculate" button must still be clicked before proceeding with model outputs. Clicking the "Calculate" button—either in manual entry or not—will give the user the option to view the system PFD or to view the power and cost summary.

3.3.3.2 System PFDs

Once the user has clicked "Calculate," either the "SWRO PFD" or the "BWRO PFD" button will appear at the top of the page, depending on the type of membrane selected. Clicking on this button will show a PFD of the system, including the ERD. The button will be hidden if system information is changed in order to prevent the PFD from showing erroneous data.

Two separate PFD configurations (SWRO and BWRO) are provided because each system has unique features. As described in Section 3.3.2.3, the SWRO system can accommodate only one- or two-stage designs, whereas the BWRO system can accommodate only two- or three-stage designs. Two ERD selections, the Pelton Wheel and the turbocharger, located before Stage 1, are used predominantly in SWRO systems. A BRWO PFD cannot be created with either of those two ERD selections.

3.3.3.3 Scenario Evaluation

The purpose of this tool is to allow the user to enter different system designs and evaluate the effectiveness of different ERDs. Similarly to the "PFD" button, once the user has clicked the "Calculate" button, the "Save Scenario" button will also appear at the top of the page. Clicking this button allows the user to give a unique name to the scenario (e.g., ERI Isobaric) and then directs the user to the "Power Summary" page to see the total power consumption of the current system design. From this page, the user can also navigate to the "Cost Summary" page. These two pages are set up to let the user compare up to ten different ERD configurations. In trying to find the best ERD for a project, the user is advised to enter in the system information, calculate the projections, save the scenario, and then repeat the steps for the alternate ERD configurations.

3.3.3.4 Power Summary

The "Power Summary" page has two tables: "Power Summary" and "Pump Summary." The "Power Summary" table shows the recently saved scenario and compares it with any previously saved scenarios. Criteria evaluated in this tool are the power requirement of each pump in the system, the total number of pumps included in the design, and the total power consumption (in horsepower and in megawatt-hours per year). If a two-pass system is chosen, the estimated additional power requirement of the second pass will be shown in the "Comments" column of this table. An acronym key is shown on the left side of the page to explain what each of the columns in the "Power Summary" table represents.

The "Pump Summary" table lists all the pumps required in the design. This tool can accommodate up to five different pumps: a high-pressure feed pump, an RO booster pump, two interstage booster pumps, and an isobaric circulation pump. For each pump included in the design, the user can enter the number of duty and standby pumps and can choose to include a VFD. Motor and VFD efficiencies can always be entered in this table, whereas pump efficiencies can only be entered for the pumps for which efficiencies have yet to be specified. If information in the "Pump Summary" table is changed, the user must click "Save Current Scenario" to update the table with the change. The "Pump Summary" table is only for the current design; it does not show information for the saved scenarios shown in the "Power Summary" table.

3.3.3.5 Cost Summary

The "Cost Summary" page has a "Cost Summary" table and several inputs required to complete the cost evaluation. Similarly to the "Power Summary" table, saved scenarios are shown and compared on the "Cost Summary" table so the most recently saved scenario can be compared against previously saved scenarios. Criteria evaluated in this table include annual power cost, ERD capital cost, ERD cost level of accuracy, ERD payback period, total RO process-mechanical cost, total annual RO process-mechanical operating cost, present worth cost (in dollars per thousand gallons of permeate), and present worth accuracy. The user can view a detailed breakdown of the ERD cost estimate by clicking the "Cost Breakdown" button.

The accuracy of the cost estimate is shown in the cost summary table. This calculation is based on the assumption that the ERD cost estimates conform to Association for the AACE Class 2 estimates (+20%/-15%), whereas the cost estimates for the rest of the system (pumps, piping, valves, membranes) are conceptual estimates and conform to Class 4 estimates

(+50%/-30%). The accuracy calculation takes into account the percentage of the ERD cost that comes from a Class 2 estimate and presents the overall accuracy. Similarly, the overall accuracy of the present worth cost takes into account the accuracy of the capital cost and operating cost. Section 3.2.3.1 discusses how the cost estimates were generated, whereas Section 3.2.4.3 discusses how the operating cost accuracy is calculated.

Inputs at the bottom of the "Cost Summary" page are needed to complete the full analysis. These inputs include standard project allowances as well as the construction start date, inflation factor, power cost, discount rate, and life cycle duration. The costs provided in this tool are in 2011 U.S. dollars (US$). Choosing the appropriate construction start date will inflate the calculated costs based on the inputted inflation rate. These inputs provide the basis for the payback period and NPV calculations.

Radio buttons are provided on the "Cost Summary" page to allow the user to select whether the ERD will be a new build or a retrofit. If the ERD is a new build, the tool will calculate the approximate cost savings associated with purchasing a smaller HPP. This is only applicable for isobaric and turbocharger applications. For Pelton Wheel ERDs, a cost is calculated for the savings associated with purchasing a smaller motor. These cost reductions are included in the payback period calculation. If the ERD is a retrofit, the user is asked if a new HPP must be purchased. This is often the case for installing an isobaric ERD, as the HPP flow is decreased by anywhere between 25% and 50%.

Similar to the "Power Summary" page, if any of the inputs are changed, the user must click "Save Current Scenario" to navigate back to the "Power Summary" or "Summary" pages. This prevents inaccurate information from being shown.

Refer to Sections 3.2.3 and 3.2.4 for details on what is included in the capital cost estimates, how the present worth calculations are executed for energy and membrane costs, and a sample of a payback period calculation.

The "Power Summary" and "Cost Summary" buttons also include an "Add No ERD Scenario" button that adds a case to the "Power Summary" and "Cost Summary" pages with no ERD. This allows the user to evaluate different ERD scenarios against a system with no ERD. Clicking on the "Clear Row" button will delete the most recently saved scenario. At all times, the scenarios shown on the "Power Summary" page are also shown on the "Cost Summary" page.

3.3.3.6 Cost Breakdown

The user can click the "Cost Breakdown" button on the "Cost Summary" page to see the different components included in the ERD cost. This typically includes the ERD device, any pumps required for ERD operation, and valves, flowmeters, and piping that are associated with the ERD. Note that only pumps specific to the ERD are included in the ERD cost, such as the isobaric circulation pump.

This page also allows the user to override any of the costs included in the ERD cost. The unit costs used in the model are shown, and an override input for each cost allows the user to enter in a more accurate cost if it is available. Costs entered include installation and inflation to the construction start year, so any override costs should be up-to-date installed costs.

A schematic of the overall cost structure is displayed on the “Cost Breakdown” page. This schematic shows the percentage of the total RO cost that is the ERD cost as well as the percentage of the ERD cost that is the device cost. Capital cost estimate accuracy ranges are also shown on the schematic.

3.3.3.7 Print Scenario

Once the user has clicked “Save Scenario” and returned to the “Summary” worksheet, the “Print” button will be visible at the top of the page. This button is only visible for recently saved scenarios and will be hidden if any of the system inputs are changed. Clicking the “Print” button will generate a print preview of the “Summary” worksheet and “Water Quality,” “Power Summary,” “Cost Summary,” and “PFD” pages for the user’s convenience.

Chapter 4

Case Studies

4.1 Introduction

Case studies of actual treatment plants were used to gather operational and design data for the energy recovery model and to evaluate the process for selecting the ERD at each facility.

The facilities presented here were selected to provide a variety of source waters and ERDs, and include two BWRO plants, one tertiary reuse facility, and two SWRO plants. The plants selected and ERDs installed are listed in Table 4.1.

Each case study had the following objectives:

- Gather all relevant cost and performance data.
- Demonstrate the benefits of the ERD in reducing energy consumption and cost.
- Evaluate and compare the operating data, cost, and energy savings.
- Highlight other noncost issues that may have been factored into the decision-making process.

The information gathered through the case studies was used to run the cost model. Cost model verification is presented in Appendix B.

Table 4.1. Facilities Selected for Case Studies

Facility/Utility	Type	ERD Installed	TDS (mg/L)	Capacity (mgd)
Eastern Municipal Water District, Perris I, CA	BWRO	ERI HTC	1500–3500	4.5
Bonita Springs Utilities, FL	BWRO	To be retrofitted with ERI HTC	3850–8000	6
Luggage Point Advanced Water Treatment Plant, Brisbane, Australia	Reuse RO	ERI HTC	1250–1500	18.5
Tampa Bay Seawater Desalination Facility, FL	SWRO	Pelton Wheel	18,500–31,000	25
Perth Seawater Desalination Plant, Kwinana, Australia	SWRO	ERI PX	36,000–37,100	38

4.2 Case Study #1: Eastern Municipal Water District, Perris I BWRO Facility

4.2.1 Basis of Selection

The Eastern Municipal Water District (EMWD) Perris I facility treats brackish well water with a TDS of 1500 to 3500 mg/L. It is a recently constructed facility that has been built incorporating modern ERDs.

4.2.1.1 Plant Description

The EMWD is located in Riverside County, east of Los Angeles in southern California. The EMWD has commissioned and constructed two desalination facilities to reduce the salt buildup in its basin and to utilize its local groundwater as a source for industrial and potable water supply. Perris I was commissioned in 2006 with a total capacity of 17,000 m^3/d (4.49 mgd).

Potable water is obtained by blending desalted water with untreated well water prior to chlorination. The desalination facility is currently fed by a system of 11 groundwater wells located within the San Jacinto basin. The quality of the brackish well water varies considerably throughout the basin, with TDS levels between 990 and 4000 mg/L.

This desalination facility includes pretreatment, a membrane RO package, chemical storage and feed systems, a decarbonator to remove CO_2 in the RO permeate, and chlorine contact equipment.

The pretreatment of the well water consists of 5-micrometer (µm) cartridge filters and chemical injection systems located upstream of the RO trains. A threshold inhibitor and sulfuric acid are used for scaling control.

Two HPPs feed two two-stage RO trains. Each train is composed of 60 pressure vessels (42 first-stage and 18 second-stage), each containing six membranes, for a total surface of approximately 14,400 m^2 (155,000 ft^2) for each train and a design-specific flux of 24.6 liters per square meter per hour (lmh) (14.4 gfd).

A decarbonator tower is installed downstream of the RO process to remove excess CO_2 in the RO permeate. Sodium hydroxide (NaOH) is added to increase the final pH for water corrosivity control.

A clear well equipped with vertical turbine pumps in a wet well provides chlorine contact capability to inactivate viruses in order to ensure that the treated water is suitable for drinking. Aqueous ammonia is injected downstream of the clear well to develop a combined chlorine residual in the finished water.

4.2.1.2 Desalination Plant Features

Table 4.2 summarizes the Perris I plant features.

Table 4.2. EMWD Perris I BWRO Plant Features

Parameter	Feature
Production capacity	18,930 m^3/d (5 mgd—4.5 mgd RO permeate + 0.5 mgd blend water)
Number of trains	2 @ 8500 m^3/d (2.17 mgd) each
Date commissioned	2006
Feed water source	Groundwater (11 wells)
Feed water TDS	1500–3500 mg/L
Product water TDS	<100 mg/L RO permeate <450 mg/L potable water
Feed water temperature	18–22 °C (64.4–71.6 °F)
Number of stages	2
Energy consumption per water produced (entire plant)	1.1 kWh/m^3 (4.16 kWh/kgal)
Operating pressure, Stage 1	9–12 barg (130.5–174.1 psig)
Operating pressure, Stage 2	11–13 barg (159.5–188.5 psig)
System recovery	70–75%
Recovery, Stage 1	50–55%
Recovery, Stage 2	35–45%
Membrane supplier	Filmtec (BW30LE-440)
Project delivery method	Design–bid–build
Capital cost	$20,000,000 (2003–2006)
Operating cost	$753,500 per year
Estimated total water cost	$0.6/$m^3$ ($2.27/kgal)
Energy recovery device	ERI HTC

4.2.1.3 Water Quality

The source water for the Perris I plant is a mix of 11 well water sources. RO permeate produced in the process can be used as either industrial water or potable water. Production of drinking water is achieved by blending the RO permeate with raw water (the ratio of raw water to permeate is 1:9) to add beneficial salts and reduce the cost of finished water production. Table 4.3 provides a summary of the plant's source water quality.

4.2.1.4 Chemical Use

Chemicals in a membrane process are typically used to manage the potential for fouling, biofouling, and scaling. At the centralized Perris I plant, the well water presents very low suspended solids, and thus cartridge filtration is sufficient to remove the turbidity.

Sulfuric acid is used to decrease the pH to 5.5–6, and a threshold inhibitor is added upstream of the cartridge filters to limit scaling. If needed to convert alkalinity to CO_2 for alkalinity reduction, sulfuric acid (H_2SO_4) can be added to the RO permeate upstream of the decarbonator tower. Excess CO_2 is then removed in the decarbonator tower. Sodium

hypochlorite (NaOCl) is added upstream of the chlorine contact tank for the final disinfection, providing a minimum of 4-log virus inactivation. Sodium hydroxide (NaOH) is added to the finished water for pH correction and corrosion control. Prior to distribution, aqueous ammonia is added to convert free chlorine to combine chlorine (chloramines.)

Table 4.3. Typical EMWD Perris I BWRO Water Quality

Constituent	Units	Feed Water	RO Concentrate	RO Permeate	Finished Water
pH	pH	6.9	—	~5	7–9
Temperature	°C	—	—	18–22	18–22
Total dissolved solids	mg/L	2375	7800	<100	<450
Total alkalinity	mg/L as $CaCO_3$	305	—	—	—
Total hardness	mg/L as $CaCO_3$	1075	—	—	—
Silica	mg/L as SiO_2	59	—	—	—
Aluminum	mg/L	0.2	—	—	—
Barium	mg/L	0.4	—	—	—
Calcium	mg/L	320	—	—	—
Iron	mg/L	0.35	—	—	—
Magnesium	mg/L	66	—	—	—
Manganese	mg/L	0.25	—	—	—
Potassium	mg/L	9.4	—	—	—
Sodium	mg/L	283	—	—	—
Strontium	mg/L	1.85	—	—	—
Bicarbonate	mg/L	301	—	20	50
Chloride	mg/L	987	—	< 60	<250
Sulfate	mg/L	338	—	< 100	<250

4.2.2 ERD Evaluation and Selection

The Perris I desalination plant was commissioned in 2006. An ERI HTC ERD was selected during design and included in the final design of the facility.

Figure 4.1 displays the PFD of the facility. The PFD is from the plant supervisory control and data acquisition (SCADA) system and shows the data on one of the RO trains in operation in April 2012.

The HTC ERD was sized based on the following plant parameters:

- RO permeate capacity flow = 4.5 mgd
- Total RO permeate flow = 4.34 mgd and raw water bypass = 0.16 mgd
- RO system recovery = 70%
- Total RO concentrate flow = 1.9 mgd= 1320 gpm
- Stage 2 concentrate pressure = 240 psig
- System line and valve losses

On the basis of these parameters, the ERD system's preliminary sizing was

- 1 unit per RO train
- 37 kW peak output, per unit
- 75% to 78% efficiency, ERD unit only

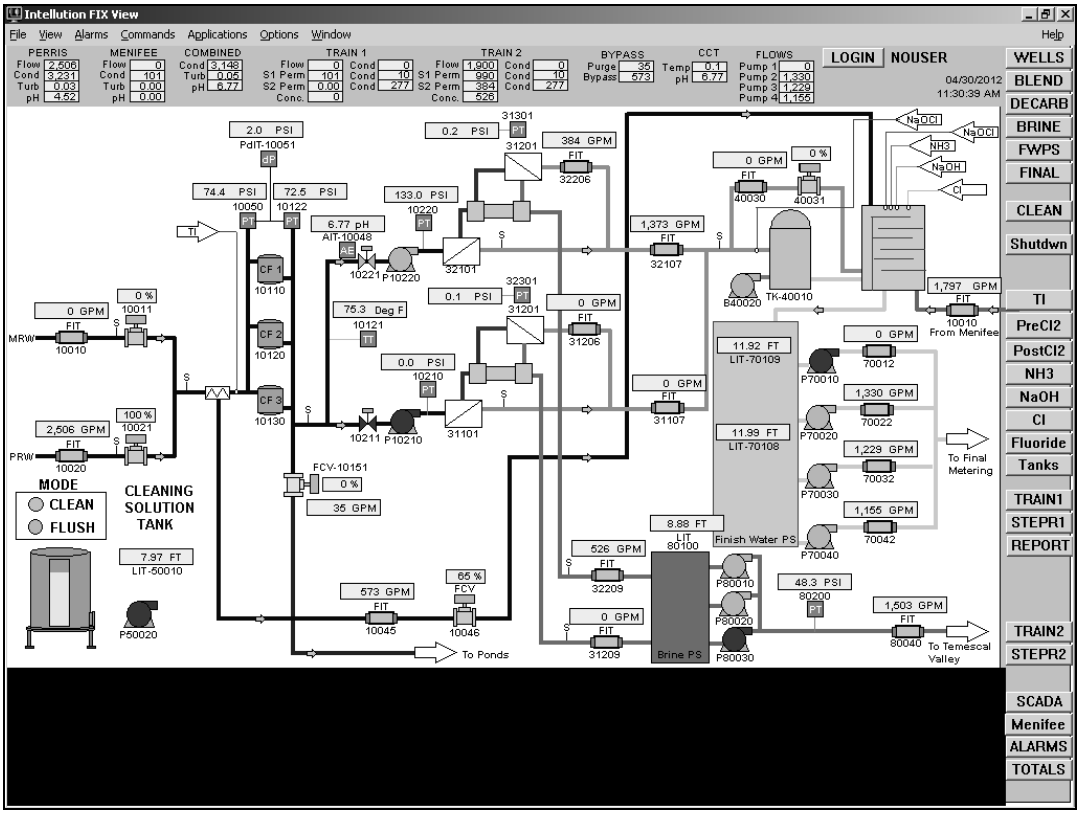

Figure 4.1. EMWD Perris I SCADA system process flow.

The engineer's estimate of ERD equipment costs for two turbines, and several other improvements including bypass valves and ERD auxiliary equipment, was $35,000 per ERD with an installation cost of $15,000 per ERD. The costs were balanced by the following energy generation assumption:

- Average operation generator output = 22 kW, 90% annual operation (330 days)
- Energy cost = $0.15 per kilowatt-hour
- Return on investment = approximately $100,000/$52,000, or 1.92 years for two ERDs, excluding design costs and maintenance costs

Each ERD discharges RO concentrate flow into a common discharge header that conveys the flow by gravity to the brine pump station.

4.2.3 Modeling Simulation of Case Study

4.2.3.1 Results of Modeling Simulation

The PFD shown in Figure 4.2, produced by the model, is representative of one of the Perris RO trains.

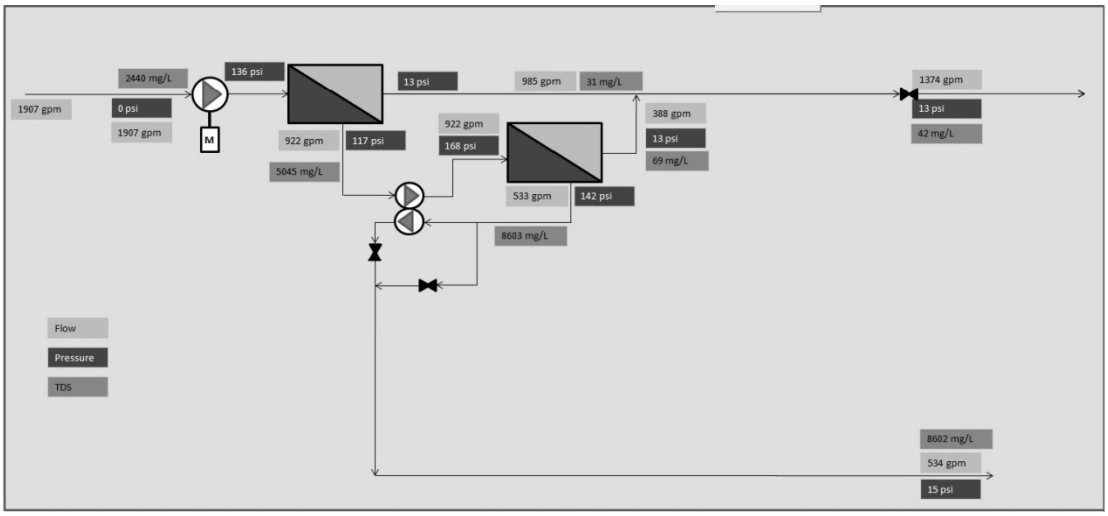

Figure 4.2. EMWD Perris I BWRO PFD.

4.2.3.2 Comparison on Model Simulation to Recorded Data

As shown in Table 4.4, the model is accurate in predicting the operating performance of the Perris I BWRO plant.

4.2.4 Conclusion

The model demonstrates that the cost of HTC^{T} ERD equipment is approximately $86,000 per RO train. This number reflects a turbocharger cost of $32,000, an additional piping installed cost of $21,000, and $38,000 in valves and instruments. The cost for the turbocharger itself is similar to the engineer's estimate presented in Section 4.2.2. However, the engineer's estimate of $50,000 per train does not appear to include all of the necessary interconnect piping valves and instrumentation.

With this level of cost estimate, it is typical to escalate the equipment cost to account for additional costs associated with installation (20%), engineering (10%), profit margin (10%), electrical costs (1%), and contingencies (10%). Therefore, the total installed ERD equipment estimate for the plant is $140,000.

The estimated power usages are 164 kW per RO train without a turbocharger, and 143 kW per RO train with the turbocharger. At $0.15 per kWh, the difference in energy savings is $28,000 per year.

Table 4.4. Model Comparison to Plant Data

	RO Feed Pressure (psi)	Permeate Backpressure (psi)	Turbocharger Boost Pressure (psi)	Reverse Osmosis (kWh/1,000 gal)
Model prediction	136	13	51	1.83
Actual operation April 2012	133	13	47	1.79

Table 4.5. EMWD Perris I BWRO Present Worth Cost and Payback Period

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal)	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Turbocharger	ERD Payback Period (years)
6%	0.31	0.29	9
3%	0.37	0.35	7
0%	0.48	0.45	5

The payback period and present worth cost of the RO equipment and energy are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and an industry standard is 25 years. Assuming an energy cost of $0.15 per kWh[3] and a present worth duration of 25 years, the tool estimates the costs and payback periods presented in Table 4.5.

An ERD payback period of less than 25 years indicates that a turbocharger is economically beneficial for the Perris I BWRO plant. The energy savings of 1.83 kWh/1,000 gal with the turbocharger versus 2.10 kWh/1,000 gal without the turbocharger overcomes the initial turbocharger capital investment.

4.2.5 Lessons Learned

At the time of the facility design, limited groundwater quality information was available. From these data, the well water quality was estimated to have a TDS range of 3000 to 7000 mg/L, with silica levels sufficiently high to limit product water recovery to 70%. After piloting and additional water quality monitoring, TDS was found to be significantly lower, varying between 1700 and 2200 mg/L. The lower TDS has resulted in lower-than-design RO train feed pressures based on the lower osmotic pressure of the well water. Consequently, pressures in the RO concentrate stream feeding the interstage HTC were lower than design, causing the turbocharger to operate outside of its design pressure range.

Because the turbocharger was sized to take a greater pressure drop across the turbine than was actually applied, the amount of interstage pressure boost was less than design, and the amount of Stage 2 concentrate capable of passing through the turbine was less than required to achieve the design product water recovery.

[3] Energy costs are based on local electrical costs and vary by case study.

To compensate for these operational deficiencies, the RO train was operated using first-stage permeate backpressure in conjunction with concentrate bypass around the turbocharger. This mode of operation is not optimal, as more feed pressure is being consumed through product water backpressure than is necessary to achieve the desired permeate flow. To minimize energy consumption while meeting RO permeate demands, the following options were evaluated and discussed with the turbocharger supplier, ERI:

- Modify existing turbochargers through replacement of nozzles and/or bypasses
- Replace turbochargers

ERI indicated that replacement of the existing turbochargers or upgrading the existing turbochargers may not offer any cost benefit compared to continued operation of the existing turbochargers as currently configured. Applying permeate backpressure to balance the flux, as practiced currently, was determined to be the best way to balance flux under lower feed TDS concentration. The results of recovery optimization testing indicated that recovery could be increased as high as 75%. This information will be shared with ERI to further assess turbocharger performance and determine the need for any modification of the existing turbochargers.

A second desalination plant, Perris II, has recently been designed for the municipality. For the Perris II system, PX, HTC, and interstage booster pump systems were evaluated based on system cost, including construction, power, and life-cycle costs. The new design incorporates higher system efficiency and better process control, as well as improved operation based on a better understanding of the feed water quality, the outcome of the Perris I optimization project, and an improved well operation strategy. Based on this comprehensive evaluation, a turbocharger was selected for use in the RO train at the Perris II plant.

4.3 Case Study #2: Bonita Springs Utilities, BWRO Facility

4.3.1 Basis of Selection

The Bonita Springs Utilities (BSU) BWRO facility, commissioned in 2004, treats brackish Floridan aquifer water using four RO trains that each produce 1.5 mgd of permeate. The RO facility has a total capacity of 6.0 mgd. The RO process removes salts from the brackish feed water.

Over the years, BSU has experienced changes in performance of the BWRO. To address these changes, BSU decided to modify the plant's RO trains. As part of the modifications, the facility will be retrofitted with ERDs.

4.3.1.1 Plant Description

The existing RO trains are designed to produce 1.5 mgd operating on a wide range of feed water qualities at an average flux rate of 14.9 gfd. The RO trains have two stages, with 24 pressure vessels in Stage 1 and 12 pressure vessels in Stage 2. Each train has a dedicated membrane feed pump with VFD and automatic concentrate control valve. The concentrate control valve and the feed pump VFD control the permeate flow and the recovery. Flux balancing between the first and second stages is accomplished by backpressuring the first-stage permeate valve. A PFD of the plant is provided in Figure 4.3.

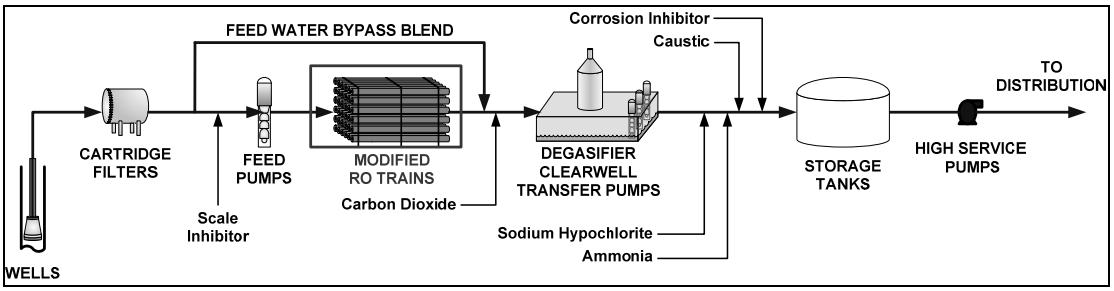

Figure 4.3. Bonita Springs Utilities BWRO plant PFD

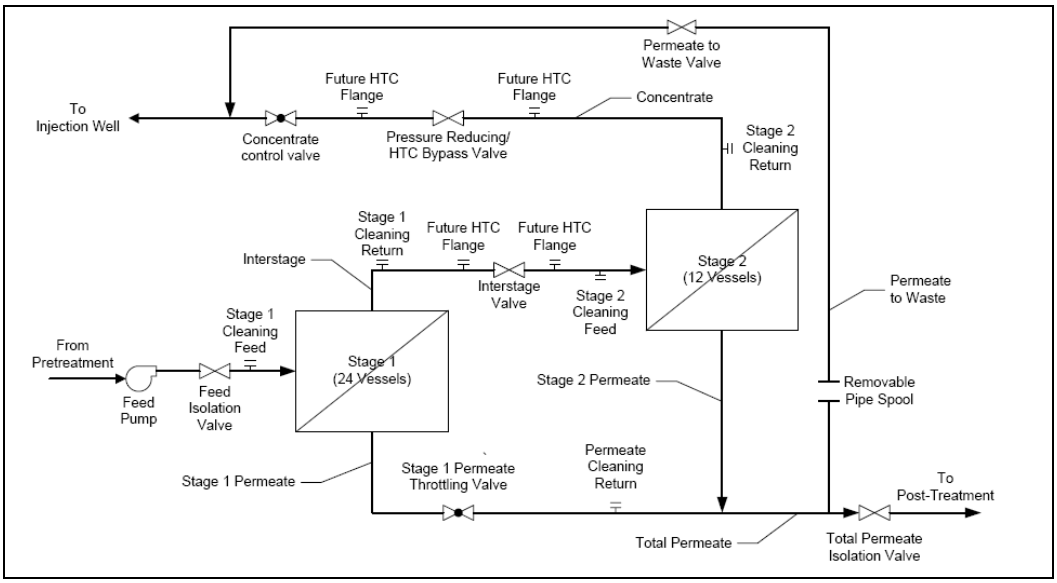

Figure 4.4. Bonita Springs Utilities RO train PFD with future HTC flanges

The original facility design included provisions to add an interstage hydraulic turbocharger ERD on each train as feed TDS increased and the economics became more favorable. Figure 4.4 shows a typical PFD for the existing RO trains.

4.3.1.2 Desalination Plant Features

Table 4.6 summarizes the BSU plant features.

4.3.1.3 Chemical Use

BSU uses the following chemicals in the BWRO treatment process:

- Scale inhibitor dosed prior to the RO membranes
- Carbon dioxide dosed post RO membranes
- Sodium hypochlorite
- Ammonia
- Caustic
- Corrosion Inhibitor dosed post the clearwell transfer pump

4.3.1.4 Water Quality

The average salinity of the existing Floridan brackish wells has been increasing since plant startup in 2004. There has been an upward trend in both chloride concentration and conductivity since early 2007. Before 2007, the well conductivity and chloride levels were relatively constant.

Table 4.6. Bonita Springs Utilities BWRO Plant Features

Parameter	Feature
Permeate capacity	6 mgd (4 RO trains @ 1.5 mgd each)
Design permeate recovery	65% to 85%
Current TDS	4684 mg/L
Max design feed TDS	8100 mg/L
Design feed pressure	200 to 460 psi
Maximum differential pressure (single stage)	50 psig
Average permeate flux	14.9 gfd
Number of pressure vessels	36
Array (Stage1:Stage 2)	24:12
Elements per pressure vessel	7
Total number of elements per train	252
Membrane element area, each	400 ft^2
Element type	High Rejection BWRO (GEWT AG8040F)
Feed pump suction pressure design range	20 – 60 psi
Feed pump primary design point	1390 gpm @ 940 ft (407 psi) TDH
Feed pump secondary design points	1225 gpm @ 982 ft (425 psi) TDH 1602 gpm @ 882 ft (382 psi) TDH
Feed pump motor horsepower	500
ERD	None initially, will be added via retrofit

The average conductivity of all of the wells has been increasing approximately 2.5% each year from 2007 to 2011. Projecting this same trend over the anticipated 10-year life of the membrane elements, the average combined well water conductivity would increase from the original 6400 micromhos per centimeter (µmho/cm) to approximately 8400 µmho/cm. This corresponds to an increase in feed TDS from the original 3,850 mg/L to approximately 5000 mg/L. The value of 5000 mg/L TDS, called the "10-year design" water quality, was used in a sensitivity analysis of membrane projections.

Table 4.7 presents the raw water quality collected in 2007. The "design" 3850 mg/L TDS water quality is also shown, along with the BSU finished water quality goals identified in the 2007 expansion design. The water quality design was used for the membrane element assessment, energy calculations, train sizing, and feed pump analysis. The 10-year design water quality was used to verify the ability of the proposed ERD and membrane selection to meet the anticipated water quality in the near future. The maximum future design water quality was also considered in the ERD design.

4.3.2 ERD Evaluation and Selection

Membrane projections were performed using projection software from multiple manufacturers to simulate the BSU RO system using both low-pressure and high-rejection

brackish water membrane elements. The analysis used the design permeate flow of 1.5 mgd per train and 80% permeate recovery with 24 first-stage vessels and 12 second-stage vessels. RO projection results are summarized in Table 4.8.

Table 4.7. Water Quality

Constituent	Units	2007 Composite Wells	Design	10-Year Design	Maximum Future Design	Finished Water Goal
pH	—	7.6	7.5	7.5	7.70	<8.5
TDS	mg/L	3,360	3850	5000	8129	<400
Calcium	mg/L	115	121	150	188	—
Magnesium	mg/L	131	124	160	300	—
Sodium	mg/L	900	1035	1300	2267	<128
Chloride	mg/L	1650	1595	2000	3950	<200
Sulfate	mg/L	652	681	850	990	<200
Total hardness	mg/L as CaCO3	830	815	1035	1700	<100
Total alkalinity	mg/L as CaCO3	164	175	175	175	>30
Temperature*	°C			15		

* Temperature use in model evaluation is noted.

Table 4.8. Membrane Element RO Train Projection Summary

Flow Stream	Flow (gpm)	Pressure (psi)
Influent	1302	0
Stage 1 feed	1302	131–208
Stage1 permeate	696–888	13–40
Stage 1 concentrate	415–606	116–198
Stage 2 feed	415–606	186–281
Stage 2 permeate	154–326	13
Stage 2 concentrate	261	176–251

The projections included a variable 47- to 120-psi interstage pressure boost between the first-stage concentrate and the second-stage feed. It was assumed that 20 psi residual concentrate pressure was needed for disposal in the injection well.

Three ERDs were considered for the BSU facility:

- ERI's HTC, Model LPT-500
- ERI's PX ERD
- FEDCO's low-pressure hydraulic energy management integration (LP-HEMI).

A new ERD will be installed on each of the four existing RO membrane trains. Figure 4.5 shows a typical turbocharger installation within each train.

Each ERD or additional booster pump[4] will be installed on a concrete pad located next to the RO train. New piping will be connected to the existing blind flanges using concentric reducers. All new piping will be Schedule 10S 316L and will be electropolished to match the existing piping. The proposed new ERD will be installed using the existing train connections and will use the existing electrical connections and instrumentation.

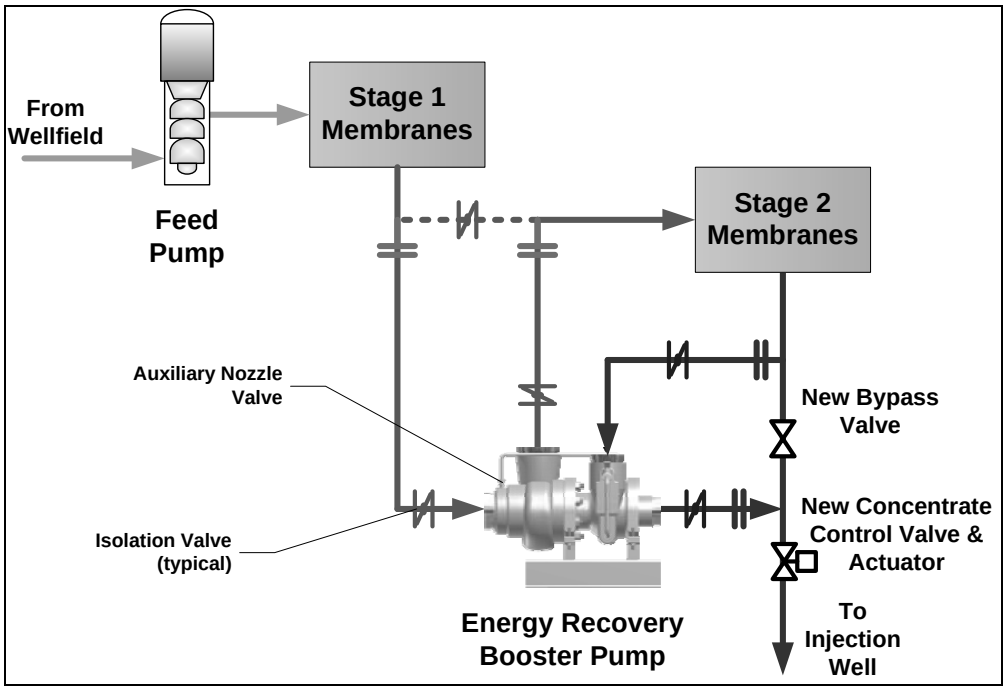

Figure 4.5. Bonita Springs Utilities turbocharger schematic.

A cost analysis was performed using the projected performance of several membrane types and the projected performance of ERI's LPT-500, LP-HEMI, and PX ERDs. The analysis included actual feed pump and well pump efficiencies, as well as estimated ERD efficiency and powered interstage feed pump efficiency for the PX and LP-HEMI options. Analysis results are presented in Table 4.9.

Table 4.9. ERD Analysis Criteria and Assumption Summary for BSU (Design)

Criteria	Design	LPT-500	LP-HEMI	PX
Well pump efficiency (%)	67%	67%	67%	67%
Well pump flow (gpm)[a]	3906	3906	3906	3906
Well pump TDH (psi)[b]	50	50	50	50
Feed pump efficiency (%)	74%	74%	74%	67%
Feed pump flow per RO train (gpm)	1302	1302	1302	1042
Feed pump suction pressure (psi)	30	30	30	30
Feed pump discharge pressure (psi)	260–300	157–208	131–196	157–208
Interstage boost pump efficiency (%)	—	—	67–72%	71%
Design interstage flow (gpm)[c]	—	510	600	510
Design concentrate flow (gpm)[c]	261	261	261	261
Interstage flow per train (gpm)	~520	415–587	503–606	453–574

[4] For FEDCO and ERI PX™ options.

Criteria	Design	LPT-500	LP-HEMI	PX
Interstage boost pressure (psi)	—	46–85	50–120	50–60
ERD efficiency (%)	—	52–60%	75–80%	88%
Net energy recovery efficiency (%)[d]	—	52–60%	54–56%	—
Unit power cost	$0.08/kWh	$0.08/kWh	$0.08/kWh	$0.08/kWh
Annual average production (mgd)	4.5	4.5	4.5	4.5

[a] Assumed average total dynamic head (TDH) of all well pumps.

[b] Assumed combined well pump flow rate for an average of three RO trains in operation at 80% recovery.

[c] Design point for peak efficiency.

[d] Accounts for both turbine-side and boost-pump-side efficiency of LP-HEMI and LPT-500.

Table 4.10. BSU ERD Power and Construction Costs

Criteria	Current	LPT-500	LP-HEMI	PX
SEC (kWh/1000 gal)	~3.80	2.28–3.06	2.14–2.94	2.26–3.13
Annual power cost ($1000)	~$500	$300–$400	$280–$386	$300–$410
Construction cost	—	$635,000	$785,000	$800,000

Table 4.10 presents SEC, estimated annual power costs, and the -30% to +50% construction costs for the proposed LPT-500, LP-HEMI, and PX ERDs. The power consumption and annual power costs were based on criteria and assumptions presented in Table 4.6. The costs reflect a 75% average plant operating factor and 80% RO system recovery. Power usage assumes operation of well pumps, RO train feed pumps, and interstage boost pumps for the PX and LP-HEMI options only.

The net power costs shown were developed for operations near the current design conditions and do not reflect the reduced efficiency if the trains are expanded in the future or if recovery is decreased.

Budgetary estimates for the PX, LPT–500, and LP–HEMI devices were provided from ERI and FEDCO. The PX estimate includes eight BPX180 devices, two units per train. The HTC estimate includes four LPT–500 devices, one unit per train. The LP–HEMI estimate includes four LPH–160/125T devices, one per train. The LPT–500 device does not have an electrical requirement; however, the LP–HEMI and PX options include a powered 30- to 40-hp interstage booster pump and required appurtenances. Ancillary equipment (piping, valves, flow meters, pressure transmitters, etc.) is also included in the estimate for each option.

All of the evaluated ERDs will reduce the annual power cost for the BSU plant. Although the PX option can save up to approximately $7000 per year depending on membrane selection, almost all membrane element options result in increased cost for the PX system. Given that the PX system is more complex to operate and has a higher up-front construction cost, the PX system was eliminated from further consideration by BSU.

Implementing the LPT-500 has a lower construction cost and will result in a lower operating cost under most operating conditions near its design flow. However, if the RO trains are expanded in the future or if the train recovery changes, the LPT-500 efficiency will decrease significantly. Alternatively, the impellers can be replaced to accommodate the new design operating conditions. The cost of new impellers for the system was approximated at $100,000.

The LP-HEMI offers significant operating flexibility and efficient operation over most potential future operating conditions without the need for modification. However, this flexibility requires additional construction cost.

The hydraulic pressure booster (HPB) from FEDCO combines the principles of the centrifugal ERD with a powered pump to add flexibility to the system. The efficiency of an HPB is similar to the efficiency of the HTC and is typically between 55% and 65%. Unlike the HTC, the HPB has a motor that can provide a pressure boost greater than what can be recovered from the brine. This capability allows better system control by providing flexibility to balance the flux between different stages without using significant backpressure. The HPB was included in the suggested selection criteria to BSU.

Table 4.11. BSU Qualitative Analysis

ERD Technology	Advantages	Disadvantages
LPT-500	Minimal maintenance requirements Previous experience at nearby RO facilities Power not required for operation	Set performance; limited flexibility in operation with varying conditions Limited efficiency over wide water quality range Less efficient than PX Bypass valve may result in high noise level
LP-HEMI	Adapts to varying system flows with minimal efficiency loss Provides better flux balancing without the need for Stage 1 permeate throttling Improves control which eliminates concentrate throttling or ERD bypass Higher efficiencies and reduced noise	Requires an electrical connection More costly than LPT-500 Less efficient than PX
PX	Reduces feed pump flow More efficient than centrifugal ERDs Low maintenance requirements	Limited application in BWRO systems Requires a powered interstage booster pump and control valve Complex control and maintenance Two units per train required Relatively large footprint Very high system noise Small increases in recovery or interstage flow will require additional units
HPB	Adaptable to new design points and increased pressure boosts Provides added flexibility to the system in flux balancing Eliminates the need for backpressure	Requires an electrical connection More costly than ERDs Has a power cost associated with pumping Less efficient than PX

A qualitative analysis was conducted on all four technologies and is presented in Table 4.11.

The LPT-500, HPB, and LP-HEMI ERDs all accomplish the same function of boosting interstage pressure using energy recovered from the waste concentrate stream. All of the options would be installed in the same location using existing blind flanges on each RO skid.

Only the LP-HEMI differs in that electrical power is needed to further boost the interstage pressure to improve efficiency. BSU will competitively bid all three ERD options and will install the option with the lowest life-cycle cost that meets the overall construction budget. Table 4.12 summarizes the BSU selection criteria.

Table 4.12. BSU Selection Criteria

Parameter	Criteria
ERD	HTC (ERI LPT-500), FEDCO HPB-500, or FEDCO LPT-12
Design interstage flow	415–700 gpm
Design concentrate flow	184–446 gpm (70% to 85% recovery at 1.5 mgd permeate)
Interstage pipe connection size	6-in.
Concentrate pipe connection size	4-in.h
Energy recovery efficiency	50% to 70%*
Projected interstage boost pressure	40–125 psi
Residual concentrate pressure	5–20 psi (based on injection well requirements)
Concentrate control valve type	Characterized seat ball valve with 480V actuator
Concentrate valve size	3-in.
Valve control	Automatic to adjust concentrate flow
Isolation valves	Manual butterfly

*Acceptable efficiency of the ERD device itself

4.3.3 Modeling Simulation of Case Study

4.3.3.1 Results of Modeling Simulation

The model produced the PFDs shown in Figures 4.6 and 4.7 for a BSU RO train operating at 75% recovery with an ERI LPT-500 turbocharger ERD and a PX ERD, respectively. The FEDCO LP-HEMI was not included in the tool, as no cost information was provided for these devices. Note that the tool does not account for the energy consumption of the well or intake pumps upstream of the high-pressure RO feed pump. Thus, to compare the RO train SEC value between the tool and the design, the incoming pressure to the high-pressure RO pump in the tool is assumed to be zero.

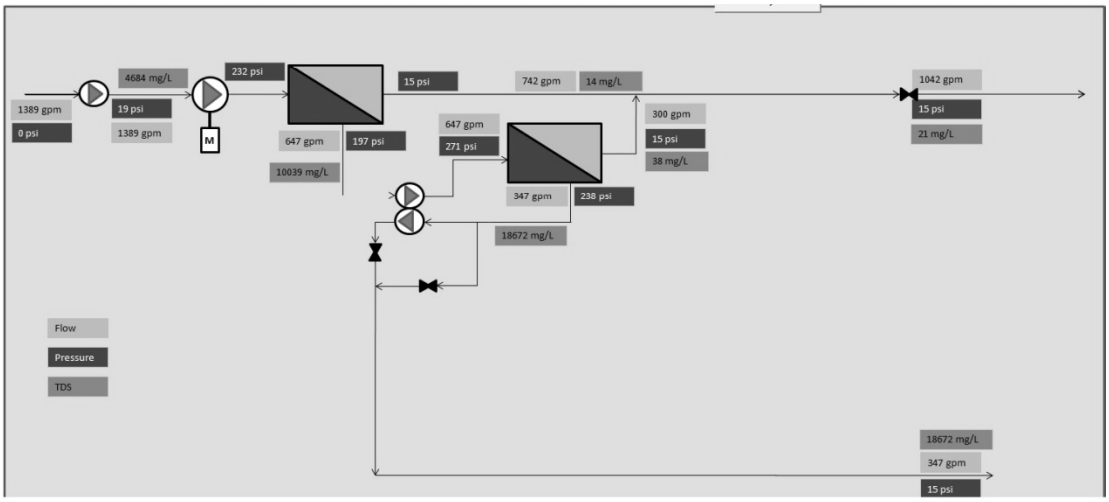

Figure 4.6. Bonita Springs Utilities RO train with LPT-500 turbocharger.

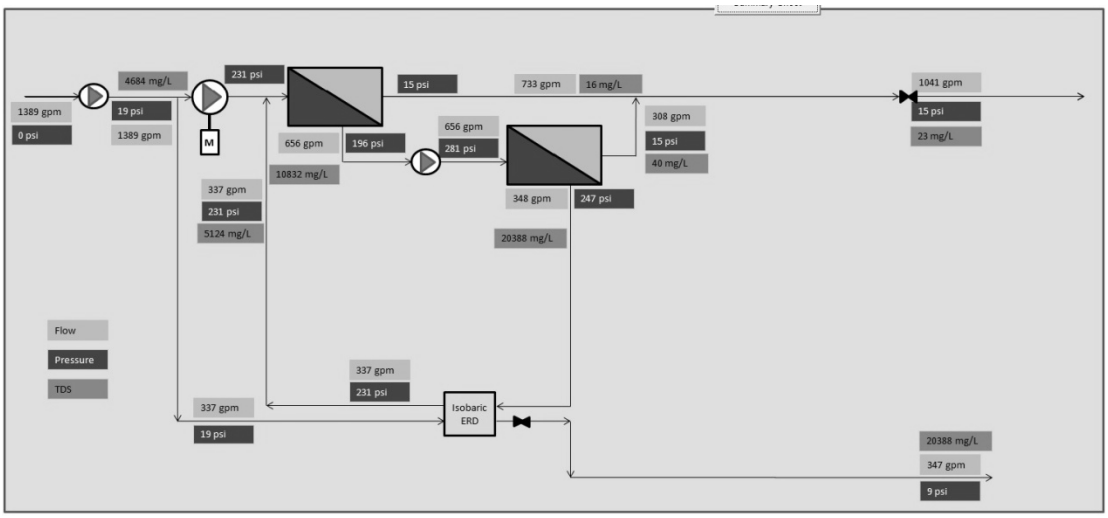

Figure 4.7. Bonita Springs Utilities RO train with ERI PX.

4.3.3.2 Comparison on Model Simulation to Actual Operation

The BWRO plant is not yet operational with an ERD; thus, no existing operational data are available for comparison. The value of this case study is in the comparison of the engineering estimates generated in order to select the appropriate ERD and similar estimates by the tool.

4.3.4 Conclusion

The tool predicts the construction costs shown in Table 4.13 for a single RO train relative to the ERD installation. The supporting equipment consists of interconnecting piping, valves, and instrumentation. The installed cost includes 53% extra for engineering profit and contingencies. The engineer's estimate for the total installed cost of all ERDs on all trains was $635,000 for the LPT-500 and $800,000 for the PX system, respectively. The estimated cost of the PX implementation is within 5% of the tool's estimate.

The tool predicts the energy costs and payback periods shown in Table 4.14 for the two ERDs. Feed pump efficiencies used in the calculations are taken from Table 4.9. The SEC values calculated by the tool are within the range of the engineer's estimate. The values calculated by the engineer include detailed analysis run by each of the ERD vendors for this particular project.

Table 4.13. BSU Construction Costs for LPT-500 and ERI-PX Model BPX-180

	Number of Devices, per RO Train	Estimated Cost of ERD and Supporting Equipment, per RO Train	Estimated Installed Cost, per RO Train	Total Estimated Installed Cost, All Trains	Engineer's Estimate
LPT-500	1	$72,000	$119,800	$480,000	$635,000
PX Model BPX-180	2	$124,300	$204,500	$818,000	$800,000

Table 4.14. BSU Energy Use with LPT-500 and ERI-PX Model BPX-180

	ERD Efficiency	ERD Efficiency (Engineer's Estimate)	Energy Use (kWh/1000 gallons)
LPT-500	64%	52–60%	3.24
PX Model BPX-180	96%	88%	3.31

The tool predicts that the estimated power usage for the BSU plant without an ERD is 232 kW per RO train. This estimate is with 15 psi permeate backpressure and does not include an interstage boost pump (which would lower this value to about 227 kW). The estimated power usages are 202 kW per RO train with the LPT-500 turbocharger and 207 kW with the PX. Based on the lower capital cost and energy cost, the tool confirms that the turbocharger is the better choice for the BSU retrofit.

The payback period and present worth cost of the RO equipment and energy use are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and the industry standard is 25 years. Assuming an energy cost of $0.08 per kWh, and a present worth duration of 25 years, the tool estimates the following costs and payback period shown in Table 4.15 for the LPT-500 turbocharger.

4.3.5 Lessons Learned

Despite the fact that the isobaric ERD, in this case the ERI PX, has a much higher efficiency than the turbocharger, the turbocharger was clearly the best selection for the BSU retrofit.

The isobaric ERDs operate in parallel to the RO high-pressure feed pump, reducing the feed pump duty flow. For retrofit of a system with an existing RO feed pump, this moves the pump off its best efficiency point. The PX retrofit would reduce the operating efficiency of the high-pressure RO feed pump to 67%.

The turbocharger, on the other hand, is a pressure booster and would not change the duty flow of the existing HPP. The pressure required by the pump would decrease, but this resulted in pump efficiency of 71%. Thus, the retrofit with the turbocharger would result in a better HPP operating efficiency.

In addition, isobaric ERD systems require not only the ERD but a separate circulating pump as well (see Figure 4.7). For smaller RO systems such as the BSU plant, the installed ERD cost for isobaric systems is comparably higher than that of a turbocharger, which does not require a separate pump. For larger RO trains, the cost of the circulating pump represents a smaller portion of the overall cost of the ERD equipment.

The LP-HEMI may indeed be the best turbocharger choice for BSU; unfortunately, cost data for these devices were not supplied by the vendor to be used in the tool.

Table 4.15. BSU Present Worth Cost and Payback Period

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) No ERD	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Turbocharger	ERD Payback period (years)
6%	0.29	0.28	10
3%	0.36	0.34	8
0%	0.46	0.43	5

4.4 Case Study #3: Luggage Point Advanced Water Treatment Plant, Water Reuse RO

4.4.1 Basis of Selection

The Luggage Point Advanced Water Treatment Plant (LPAWTP) was constructed in response to a period of unprecedented population growth in Brisbane and South East Queensland, Australia, combined with a prolonged drought from 2002 to 2008, which created an acute shortage of water in the region.

The LPAWTP treats secondary effluent from the adjacent Luggage Point Wastewater Treatment Plant (LPWWTP) to a level that meets drinking water quality standards to augment the city of Brisbane's largest potable water source, Lake Wivenhoe, and to provide high-quality water to two power plants.

4.4.1.1 Plant Description

The LPAWTP uses a multibarrier treatment approach that includes chemically assisted clarification, microfiltration (MF), RO, and ultraviolet disinfection/advanced oxidation (UV/AOP) to treat secondary wastewater effluent from the LPWWTP. Raw water from the wastewater plant is first pumped to raw water storage tanks at the LPAWTP site. The raw water then goes through flocculation and clarification, with ferric chloride used as a coagulant. The clarified water is pumped to the MF system,further treated by RO and UV/AOP, and then chemically stabilized. Preformed chlorimines are dosed either ahead of flocculation or prior to the MF system.

Sludge generated in the clarifiers and the MF prescreens is directed to a gravity thickener that is dewatered by centrifuges. MF backwash water is chemically clarified using a dedicated system, and the supernatant returned to the raw water storage tanks.

Figure 4.8 presents a schematic of the overall plant treatment processes.

The RO system at the LPAWTP has an annual average capacity of 17.4 mgd (66 million liters per day [MLD]) and a maximum daily output of 18.5 mgd (70 MLD).

The RO system consists of four trains (three duty and one standby). The design recovery of the overall RO plant is 85%. To achieve 85% recovery, a three-stage system is used. The RO process flow is shown in the PFD in Figure 4.8.

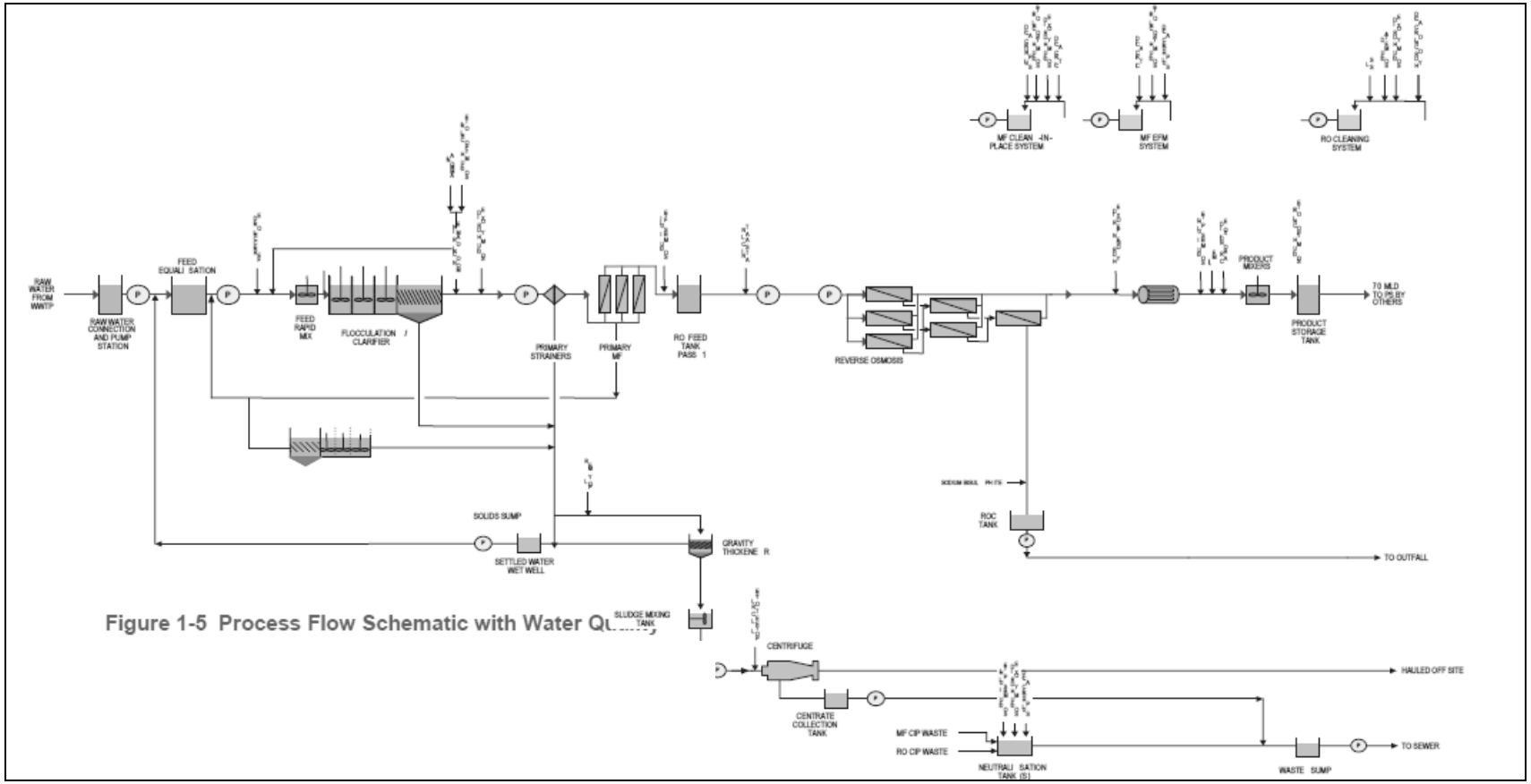

Figure 1-5 Process Flow Schematic with Water Qu

Figure 4.8. Luggage Point AWTP PFD.

Table 4.16. Reverse Osmosis Design Criteria

Parameter	Feature
Maximum permeate capacity	18.5 mgd (70 MLD)
Trains	4 (3 online/1 standby)
Overall design permeate recovery	85%
Maximum design feed TDS	1500 mg/L
Design feed pressure	319 psi (2200 kilopascals [kPa])
Average permeate flux	10.5 gfd (17.8 lmh)
Stage 1 permeate backpressure and design backpressure valve	60 psi (414 kPa)
Design temperature (minimum)	19 °C
Number of pressure vessels installed per train	210
Array (Stage1:Stage 2:Stage 3)	120 × 60 × 30
Elements per pressure vessel	7
Total number of elements per train	1470
Element manufacturer and model	Toray, TML20-400 BWRO
Membrane element area	400 ft^2
Number of RO booster pumps	3 duty/1 standby
RO booster pump design point (each)	Maximum—5040 gpm (318 L/s) @ 30 psi (210 kPa) TDH Minimum—3994 gpm (252 L/s)
RO booster pump horsepower	450 hp (335 kW)
Number of RO Feed pumps	3 duty/1 standby
RO feed pump design point (each)	5040 gpm (318 L/s) @ 320 psi (2200 kPa) TDH
RO feed pump suction pressure	43.5—101.5 psi (300—700 kPa)
RO feed pump motor horsepower	845 hp (630 kW)

Each RO process train consists of one RO booster pump, one cartridge filter, one feed pump, and one membrane skid. Antiscalant is dosed prior to cartridge filtration to limit scaling.

4.4.1.2 Reverse Osmosis Plant Features

Table 4.16 presents the RO design criteria for the LPAWTP.

4.4.1.3 Water Quality

The RO system receives secondary treated (clarified and microfiltered) effluent. The purpose of the RO system is to reduce the concentration of dissolved inorganics and organics in the feed water, as well as provide one of three barriers to pathogens. The RO feed water pH is in the range from 6.5 to 7.3 because of ferric dosing in the flocculation/coagulation process. The phosphate is reduced in the clarification process, and solids are removed in the MF process. Organics reduction is approximately 30% to 50% through clarification and MF.

Table 4.17 summarizes the RO feed water quality.

Water produced at the LPAWTP is designed to meet the water quality standards listed in Table 4.18.

Table 4.17. Reverse Osmosis Feed Water Quality

Constituent	Units	90th Percentile Concentration	50th Percentile Concentration
Calcium	mg/L	46	42
Magnesium	mg/L	48	39
Sodium	mg/L	422	333
Potassium	mg/L	32	27
Barium	mg/L	0.022	0.017
Ammonia	mg/L	0.66	0.13
Aluminum	mg/L	0.06	0.03
Iron, total	mg/L	0.17	0.13
Manganese, total	mg/L	0.14	0.11
Copper	mg/L	640	530
Sulfate	mg/L	120	100
Nitrate	mg/L	22	11
Bicarbonate	mg/L	224	198
Carbonate	mg/L	0.10	0.04
Phosphate	mg/L	6	3
Fluoride	mg/L	1.4	0.9
Silt density index (SDI) (15 min)	mg/L	<3.0	
Conductivity	µS/cm	2600	2040
TDS (sum)	mg/L	1500	1250
Temperature	°C	30	25
pH	–	7.0	6.6
Silica	mg/L	11	10
Total suspended solids	mg/L	<1.0	<1.0
Turbidity	NTU	<0.3	<0.1
Biochemical oxygen demand	mg/L	5	2.5
Total Kjeldahl nitrogen	mg/L	3.3	2.0
Organic nitrogen	mg/L	7.0	5.0
Nitrate as N	mg/L	4.7	2.8
Total phosphorus	mg/L	2.0	1.0

Table 4.18. Water Quality Goals

Constituent	Units	Water Quality Standard	Statistical Basis
Total nitrogen	mg/L	0.8-1.2	Annual 50th Percentile
Total phosphorous	mg/L	0.13	21 day, 50th Percentile
Clostridium perfringens—median	cfu/100 mL	1	Annual
Clostridium perfringens—95th percentile	cfu/100 mL	10	Annual
Hardness as $CaCO_s$	mg/L	>50	21 day average
Alkalinity	mg/L	>40	21 day average
Calcium carbonate precipitation potential	—	0 to -5	Maxima/minima
Total organic carbon	mg/L	1	Maximum
Nitrododimethylamine	ng/L	10	Values to be less than or equal to the value listed in 90% of samples
Estrone	ng/L	3	Values to be less than or equal to the value listed in 90% of samples
17-beta estradiol	ng/L	1	Values to be less than or equal to the value listed in 90% of samples
Ethinylestradiol	ng/L	0.1	Values to be less than or equal to the value listed in 90% of samples
Total predicted no-effect concentration	ng/L	1	Values to be less than or equal to the value listed in 90% of samples
Nonylphenol	ng/L	7	Values to be less than or equal to the value listed in 90% of samples

4.4.1.4 Chemical Use

Fourteen chemicals are used at the LPAWTP site for all the processes. The chemicals and the associated feed points are as follows:

- Ferric chloride, clarification
- Sodium hydroxide, MF cleaning, RO clean in place (CIP), neutralization
- Aqueous ammonia, clarification/MF feed, chloramination
- Sodium hypochlorite, clarification/MF feed (chloramination), finished water, MF cleaning
- Sodium bisulfite, finished water, MF/CIP neutralization, MF filtrate
- Hydrogen peroxide, UV influent
- Carbon dioxide, finished water
- Antiscalant, RO first pass
- Sodium lauryl sulfate, RO CIP
- Hydrochloric acid, RO CIP
- Citric acid, MF CIP, RO cleaning

- Sulfuric acid, MF CIP, neutralization, MF cleaning
- Polymer, clarification, centrifuge dewatering, thickening MF backwash system
- Lime, finished water

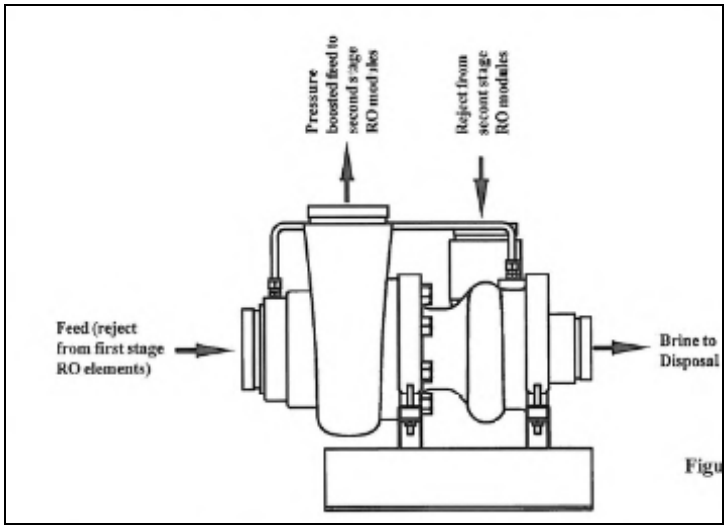

Figure 4.9. Flow streams for a turbocharger.

4.4.2 ERD Evaluation and Selection

Four ERI HTCs, one per RO train, are installed at the LPAWTP. The HTC provides a pressure boost between second-stage concentrate and third-stage feed. The third-stage reject is used for pressure boost. Figure 4.9 illustrates typical streams for a turbocharger.

Information on the ERDs at the LPAWTP is summarized as follows:

- ERD type: HTC
- Number of ERDs: four (one on each train)
- Manufacturer: ERI
- Model: LPT-2000
- Maximum operating pressure: 600 psi

The HTCs enable a reduction in the size of the RO feed pump motors to 845 hp (630 kW), thereby providing lower operating costs and the ability to balance flux rates in each stage to reduce the fouling potential.

A detailed quantitative analysis of energy recovery was not conducted during the design phase of the LPAWTP. Turbocharger ERDs were selected because of the number of installations and reliability, and the devices have proven to be effective. An ERD installation at the plant is shown in Figure 4.10.

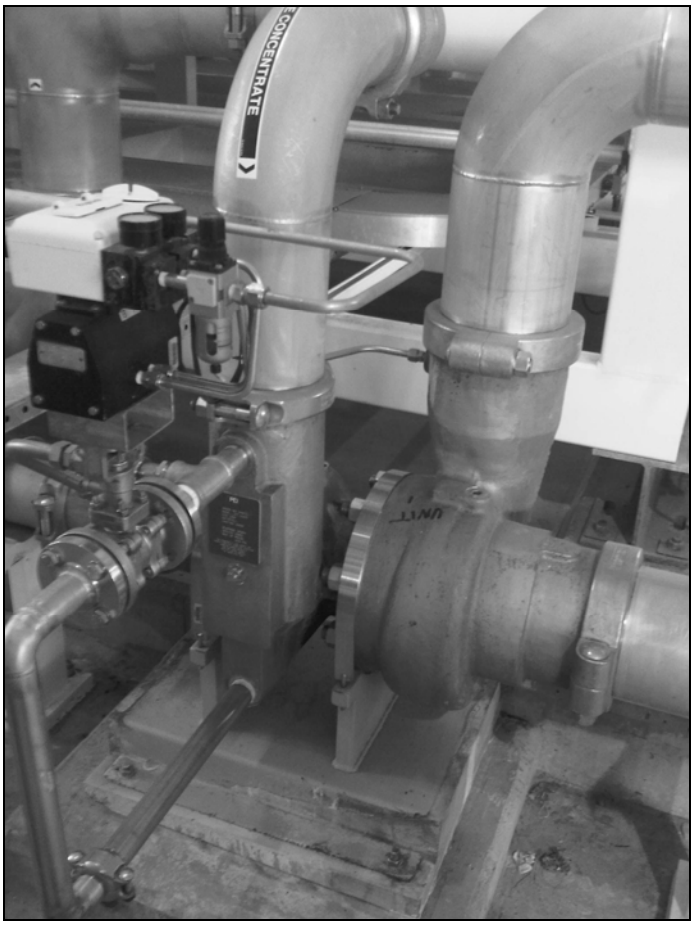

Figure 4.10. Turbocharger installation at LPAWTP.

4.4.3 Modeling Simulation of Case Study

4.4.3.1 Results of Modeling Simulation

LPAWTP has a three-stage RO system. For multistage RO systems, the turbochargers are typically installed between stages to provide a multistage boost and therefore a higher net driving pressure for downstream stages. This has the benefit of providing additional balance to the individual stage flux rates in the RO train. Hypothetically, a turbocharger could be installed to boost the feed to the entire system, but this is rarely done. Turbocharger efficiencies, as explained in Chapter 3, are heavily influenced by the reject ratio, which is the ratio of the concentrate flow over the boosted flow (the feed flow in this case). If this ratio is substantially lower than 50%, the efficiency of the turbocharger suffers. If the recovery of the RO system is 60% or higher, the reject ratio for boosting the RO feed will be 40% or lower.

Therefore, in a three-stage system, the turbocharger can be inserted before either the second or third stage. The tool provided the PFDs shown in Figures 4.11, 4.12, and 4.13 for single RO trains for the LPAWTP with no turbocharger, turbocharger insertion upstream of the second stage, and turbocharger insertion upstream of the third stage, respectively.

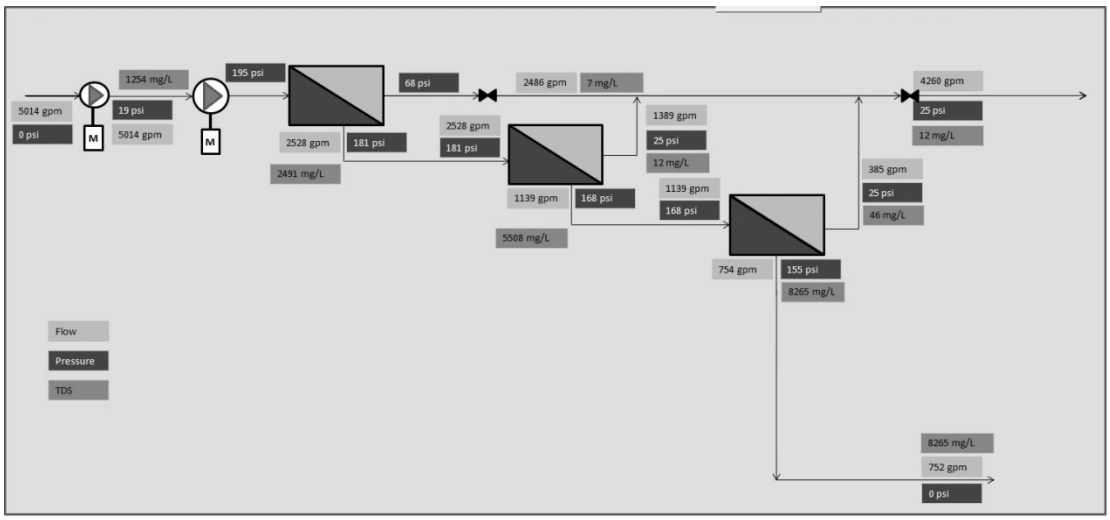

Figure 4.11. Tool PFD of LPAWTP RO train.

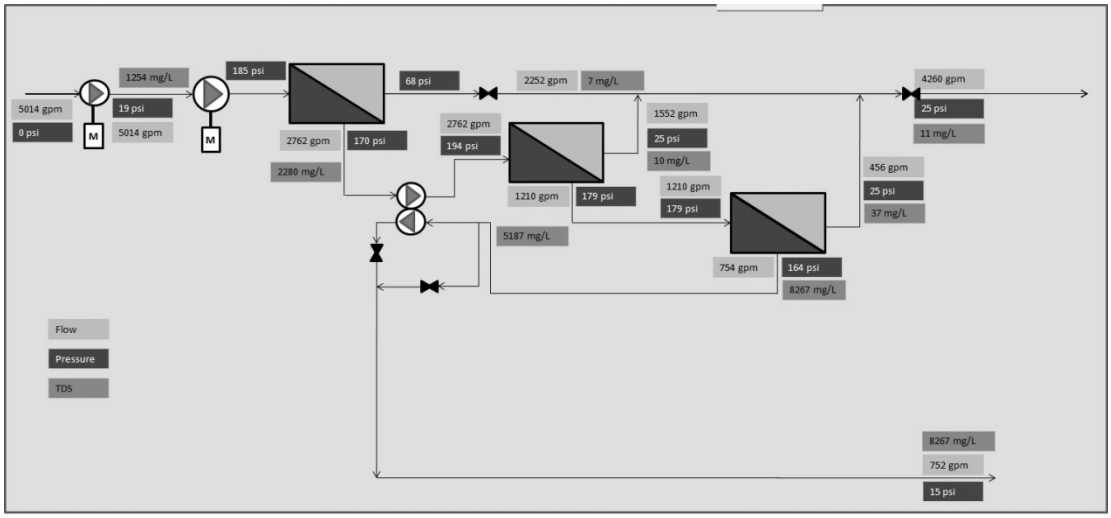

Figure 4.12. Tool PFD of LPAWTP RO train with turbocharger upstream of Stage 2.

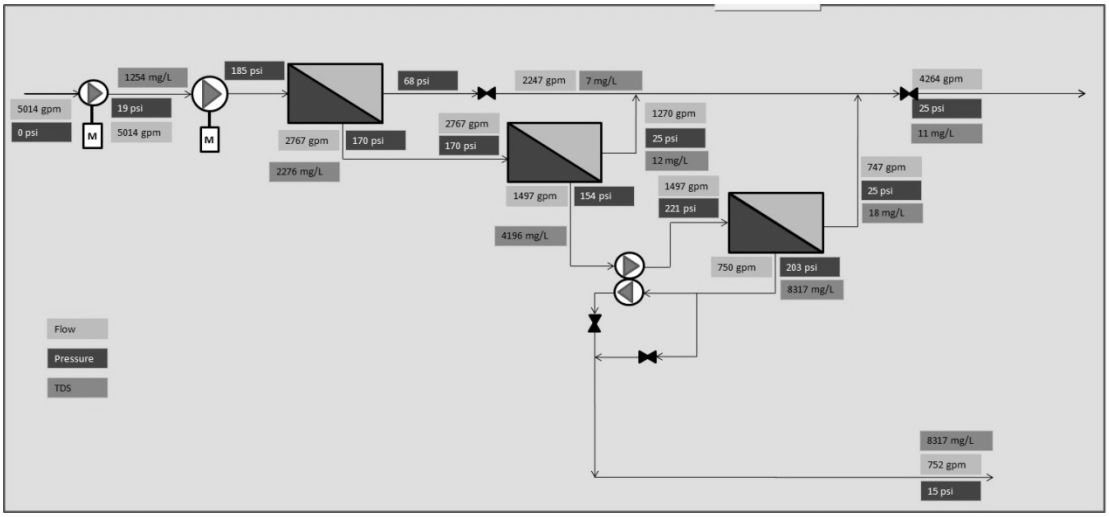

Figure 4.13. Tool PFD of LPAWTP RO train with turbocharger upstream of Stage 3.

4.4.3.2 Comparison of Tool Simulation to Actual Operation

The turbocharger was installed as a boost to the third stage. A snapshot of the actual data from the site taken June 8, 2011 is shown in Figure 4.10 and compared with the operation predicted by the tool. The operational permeate backpressure is 25 psi, and an additional 43 psi is applied to the first stage for flux balancing. Actual permeate flow, feed temperature, and recovery were 4262 gpm, 21 °C, and 80%, respectively.

4.4.4 Conclusion

The tool estimates that the power usages at the LPAQTP are as follows:

- 544 kW per RO train without a turbocharger
- 514 kW per RO train with the turbocharger placed before either the second or third stage

At $0.08 per kWh, the difference in energy savings is approximately $21,000 per year.

With this amount of energy savings, the question is whether it is really worthwhile to add a turbocharger to the system, and, if so, where to place it. These questions can be answered by comparing the present worth of RO equipment and energy, as well as the ERD payback period. The payback period and present worth cost of the RO equipment and energy use are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and the industry standard is 25 years. Assuming an energy cost of $0.08 per kWh, and a present worth duration of 25 years, the tool estimates the costs and payback period presented in Table 4.20.

Table 4.19. Luggage Point Snapshot vs. Tool Prediction

Constituent	Units	Actual Operation	Tool Prediction
First-stage feed pressure	psi	176	185
First-stage concentrate flow/pressure	gpm/psi	2551/159	2767/170
Second-stage concentrate flow/pressure	gpm/psi	1411/146	1497/154
Third-stage feed/ turbocharger boost pressure	psi/psi	218/72	221/67

Table 4.20. Present Worth Cost and Payback Period

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1000 gal)	Present Worth Cost of RO Equipment and Power ($/1000 gal) with Turbocharger Before Second or Third Stage	ERD Payback Period (years) with Turbocharger Before Second/Third Stage
6%	0.23	0.22	23/12
3%	0.27	0.26	17/9
0%	0.34	0.33	12/6

Based on the present worth costs, it is not apparent that the addition of a turbocharger to the LPAWTP is economically beneficial. However, close examination of the ERD payback period shows that turbocharger implementation is economically beneficial, as the payoff occurs before the life of the equipment ends, regardless of the discount rate assumed during the present worth duration. The reason for the difference in payback period between stages is that the turbocharger size and cost are related to the quantity of the flow that is boosted. This flow is lowest in front of the third stage. For the LPAWTP, the difference in installed capital cost between placing the turbocharger in front of the second stage or the third stage amounted to about $110,000, with $70,000 of this attributed to the smaller turbocharger cost. This savings tipped the balance in favor of placing the turbocharger in front of the third stage of the system.

The comparison between the actual operating data and the tool (Table 4.19) indicate that the predicted membrane feed pressure and turbocharger boost pressures are accurate within 5% and 7%, respectively.

4.4.5 Lessons Learned

The efficiency of a turbocharger is strongly influenced by the reject ratio and the boosted flow. For these reasons, it is typical to place the turbocharger between stages in a multistage RO train and, in most cases, before the last stage of the RO train.

4.5 Case Study #4: Tampa Bay Water, Desalination Plant

4.5.1 Basis of Selection

Tampa Bay Water is Florida's largest wholesale water provider. The Tampa Bay Seawater Desalination Facility (TBSDF) is one of the treatment facilities it operates.

4.5.1.1 Plant Description

The TBSDF is located near Apollo Beach in southern Hillsborough County. It is currently the largest operating SWRO facility in North America, with an average capacity of 25 mgd. The plant consists of the following treatment process trains:

- Raw water screening
- Coagulation and flocculation systems
- Single-stage sand filtration system followed by diatomaceous earth precoat filtration system
- Chemical storage and feed systems
- Residuals treatment system
- SWRO system

The basis of design for the pretreatment unit processes has been to meet the following water quality goals for the RO feed water:

- Turbidity < 1.0 NTU
- SDI < 4.0
- pH 6.5

Additional pretreatment goals include:

- SDI_{15} < 2 with a standard deviation of 1
- Particle counts 2-3 µm (per mL) < 50
- Total iron (µg/L) < 20

The TBSDF has been designed with a minimum permeate production capacity of 8 mgd, an average flow of 25 mgd, and a maximum flow of 28.75 mgd.

TBSDF consists of a two-pass RO system. The first pass has seven trains, with six of the trains used to meet the average 25-mgd production. The seventh first-pass train is used when the maximum flow of 28.75 mgd is required.

Each first-pass RO train includes the following components:

- 5-µm cartridge filter
- High-pressure feed pump
- RO membrane skid
- Pelton-Wheel-type energy recovery turbine

The second pass has six trains. The number of online trains depends on the chloride level in the first-pass permeate, which in turn is a function of feed water salinity, temperature, and membrane flux.

The profile of ions in the feed water remains relatively constant over the range of salinity. The variation in feed water salinity is attributable to the dilution effects of brackish rivers, creeks, and rainfall.

A schematic for the plant's pretreatment process is presented in Figure 4.14. The RO system schematic is included in Figure 4.15.

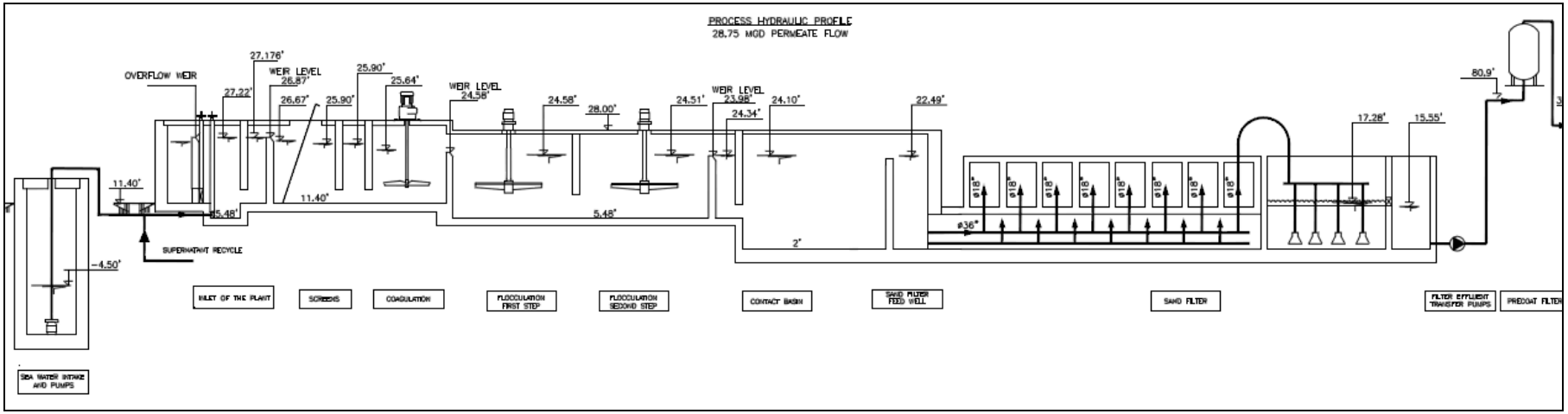

Figure 4.14. TBSDF pretreatment PFD.

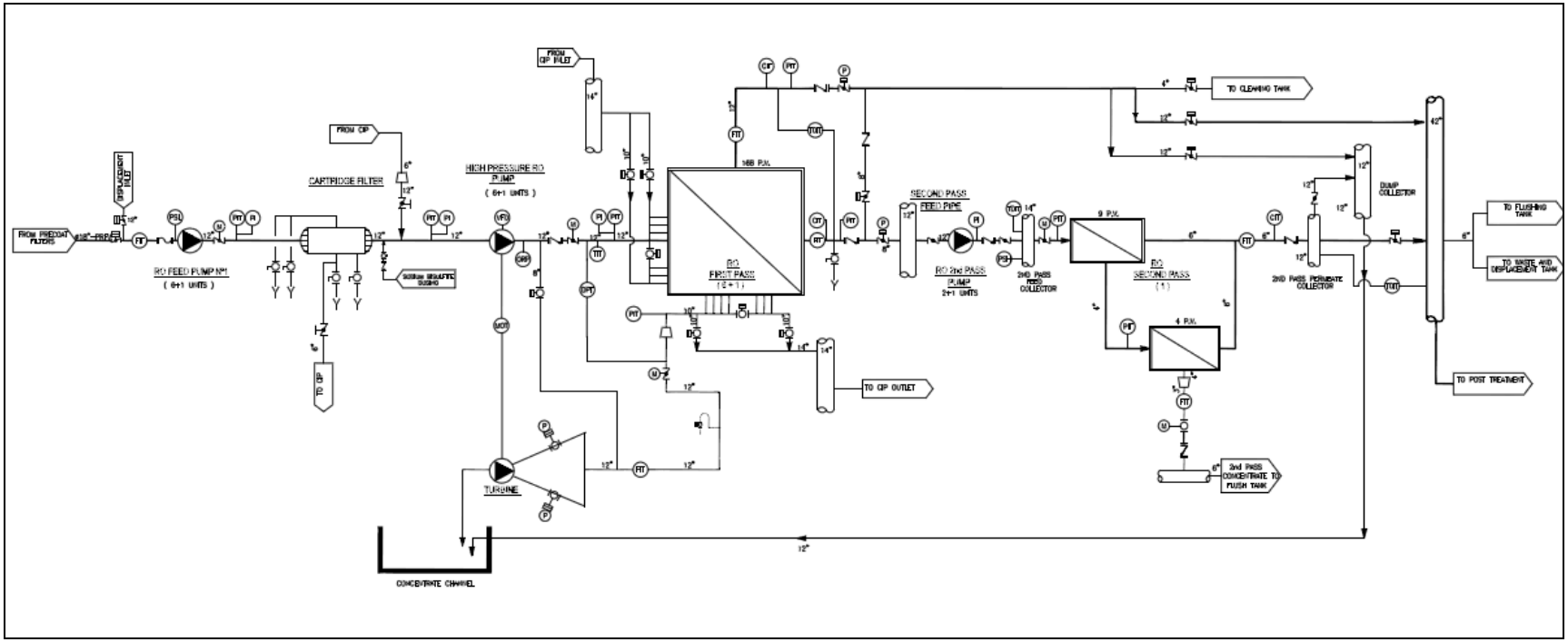

Figure 4.15. TBSDF RO system PFD.

Table 4.21. TBSDF Reverse Osmosis Plant Features

Parameter	Units	First Pass	Second Pass
Permeate capacity	mgd (m^3/d)	25 (95,000)	
Number of trains	trains	7	6
Design permeate recovery	%	60	90
Design feed TDS	mg/L	18,500–31,000	700–2200
Design feed pressure	psi (kPa)	564–985 (3889–6791)	126–250 (869–1725)
Average permeate flux	gfd (lmh)	8.5 (14.5)	11–23 (18.7–39.1)
Number of pressure vessels per train	vessels	168	13
Array	array	168	9 × 4
Elements per pressure vessel	elements	8	8
Total number of elements per train	elements/train	1344	104
Membrane element area, each	ft^2	380	380
Element type		SW30HR-380	SW30HR-380
Number of RO feed pumps	pumps	7	3
Feed pump motor horsepower	HP	2000	450
Feed pump capacity	gpm	4907	2130
Energy recovery device	—	Pelton Wheel	N/A

4.5.1.2 Desalination Plant Features

Table 4.21 summarizes the features of the TBSDF.

4.5.1.3 Water Quality

Table 4.22 presents the feed water quality assumed for the TBSDF design.

Water quality standards have been assigned by Tampa Bay Water to define the specific treatment requirements and the basis of design for the TBSDF. The contractual standards are more stringent than local and federal drinking water standards. Table 4.23 lists the product water quality parameters.

Table 4.22. TBSDF SWRO Feed Water Design Values

Parameter	Units	Source Water Quality
pH	—	8.5
Total dissolved solids	mg/L	31,000
Turbidity	NTU	15
Temperature	°C	15
Chloride	mg/L	18,000
Calcium hardness	mg/L as $CaCO_3$	900
Bromide	mg/L	1.2

Table 4.23. TBSDF Product Water Quality Contract Standards

Parameter	Units	Contractual Standard
Antimony	mg/L	0.006 (max)
Arsenic	mg/L	0.01 (max)
Asbestos	mg/L	7 (max)
Barium	mg/L	2 (max)
Beryllium	mg/L	0.004
Cadmium	mg/L	0.005
Chromium	mg/L	0.1
Cyanide	mg/L	0.2
Fluoride	mg/L	0.8
Lead	mg/L	0.015
Mercury	mg/L	0.002
Nickel	mg/L	0.1
Selenium	mg/L	0.05
Sodium	mg/L	80
Thallium	mg/L	0.002
Microbiological—total coliform	CFU/100 mL	<1
Radiochemical—gross alpha	pCi/L	5
Turbidity	NTU	0.3
Aluminum	mg/L	0.2
Chloride	mg/L	100
Copper	mg/L	1.0
Iron	mg/L	0.15
Manganese	mg/L	0.05
Silver	mg/L	0.1
Sulfate	mg/L	100
Zinc	mg/L	5
Color	PCU	15
Odor	TON	2 (max-avg)/3 (max)
pH		7.4 (min-week-avg)
Total dissolved solids	mg/L	500
Foaming agents	mg/L	0.5
Conductivity	µmho/cm	850
Temperature	°C	35
Total alkalinity	mg/L as CaCO3	40 (min-avg)
Total sulfide	mg/L	0.1 (avg)
Total hardness	mg/L as CaCO3	300
Calcium hardness	mg/L as CaCO3	50 (min-avg)/250 (max-avg)
TOC	mg/L	3.6 (max-avg)/6.6 (max)
Total phosphorus	mg/L	1
Ortho phosphorus	mg/L as P	1
Ammonia	mg/L as N	1
Assimilable organic carbon	µg/L	100
Heterotrophic plate count	CFU/ 1 mL	5
Bromide	mg/L	0.45
Chlorine residual	mg/L	4.0

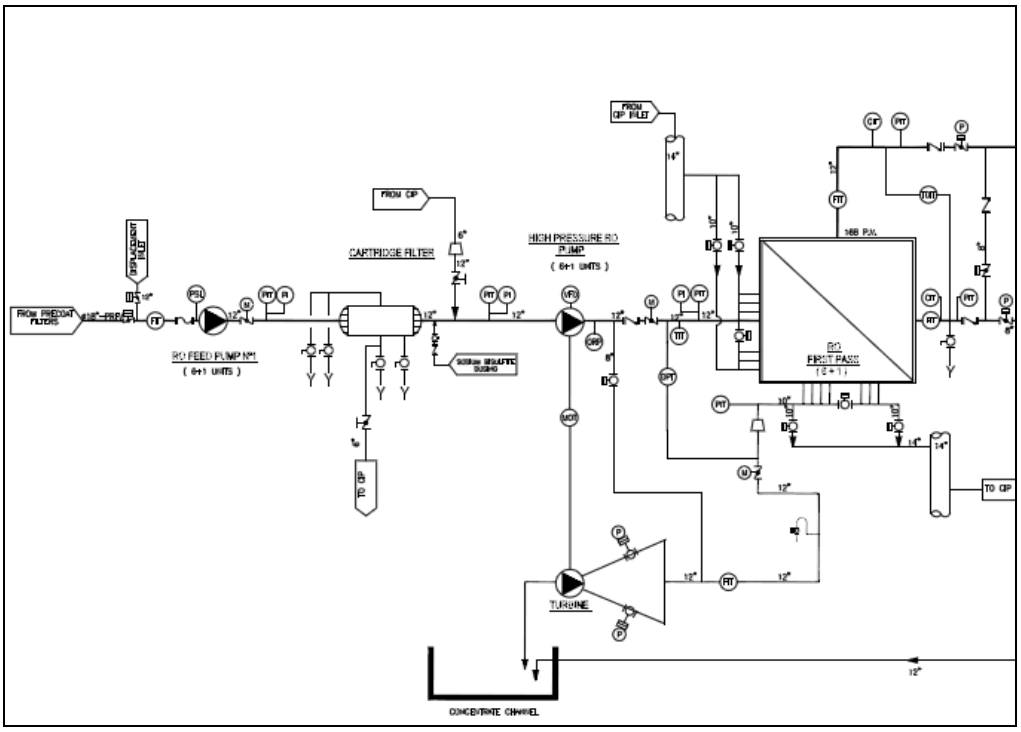

Figure 4.16. TBSDF ERD schematic.

4.5.1.4 Chemical Use

The following chemicals are used in the TBSDF treatment process:

- Chlorine dioxide, intake and RO permeate
- Ferric sulfate, before filters
- Polymer (if required), sand filter influent
- Sulfuric acid, RO feed
- Sodium bisulfite, RO feed
- Lime, RO permeate

4.5.2 ERD Evaluation and Selection

A Pelton-Wheel-type ERD is used at the TBDSF. The ERD is fed by the first-pass concentrate. A schematic of the ERD is shown in Figure 4.16.

The selection of the Pelton Wheel ERD was largely driven by lack of an established experience base for isobaric devices of sufficient capacity at the time the plant was initially designed. During the initial design, conducted by Stone & Webster in 1999, an evaluation of ERD technology was conducted. Based on the evaluation, no isobaric devices of sufficient capacity were available that had sufficient experience to manage the risk. The first installation of PX units was in 1997, with no sizable installations prior to Tampa Bay.

Each high-pressure feed pump at the TBSDF utilizes a Pelton-Wheel-type ERD manufactured by Calder AG, Model RO-350-100-2. The ERD produces energy by recovering the excess high-pressure energy in the first-pass concentrate stream before it is discharged. Each ERD is driven by concentrate flow at a variable pressure range of 572 to 970 psi.

The ERD installed allowed a 27% reduction in the high-pressure feed pump motor sizing. During the design phase, it was estimated that a 28% to 32% energy cost reduction would be achieved in the operation of the first-pass RO system. This equated to an energy cost savings of 24% to 28% in the entire plant operation. The ERDs at the TBSDF are believed to be 86% to 88% efficient.

4.5.3 Modeling Simulation of Case Study

4.5.3.1 Results of Modeling Simulation

The TBSDF operating staff reports that the energy use of a single RO train is approximately 1325 kW in May 2012 under the following conditions:

- 2750 gpm permeate flow
- 58.5% recovery
- Membrane feed pressure 950 psig
- HP RO feed pump suction pressure 200 psig

Under these conditions, the tool produces the PFD shown in Figure 4.17 of a sample TBSDF first-pass RO train with a Pelton Wheel ERD.

4.5.3.2 Comparison of Model Simulation to Recorded Data

The tool predicts that the energy use of the RO feed pump/Pelton Wheel combination will be 1355 kW operating under the conditions listed in Section 4.5.3.1. This is within 4% of the value reported by the operating staff of the plant.

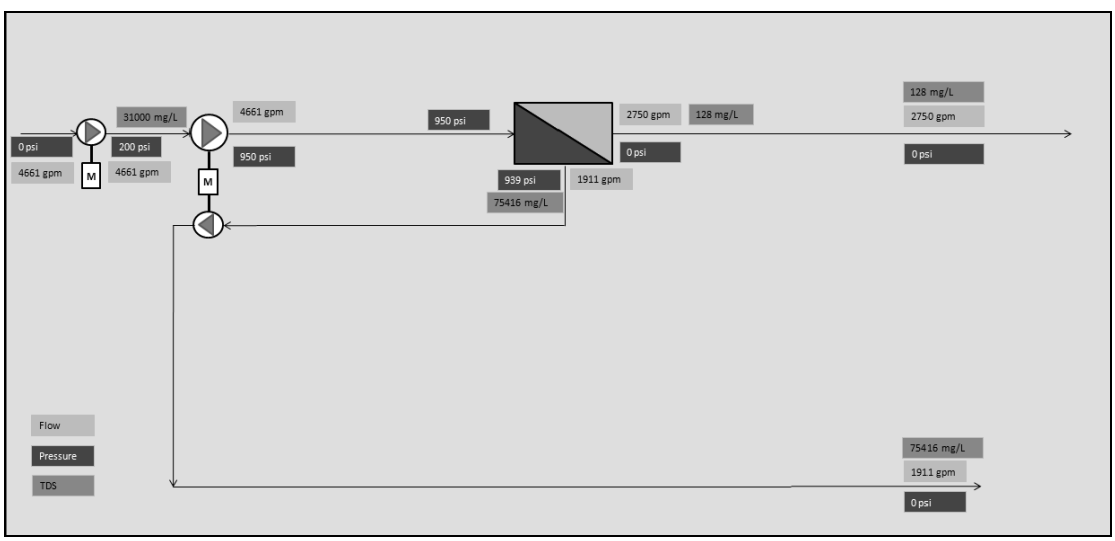

Figure 4.17. Model PFD of Tampa Bay first-pass RO train with Pelton Wheel.

Table 4.24. TBSDF First-Pass Reverse Osmosis Model Prediction

	ERD Efficiency	Energy Use (kWh/1,000 gal)	Percent Reduction in Energy Use
No ERD	N/A	15.1	N/A
Pelton Wheel Calder RO-350-100-2	88%	10.9	28%
Isobaric ERD	98%	9.8	35%

4.5.4 Conclusion

The tool predicts energy use of the individual TBSDF RO trains as shown in Table 4.24.

According to the tool, the Pelton Wheel lowers the energy use of the RO by 28%, which is within the estimated range of 28% to 32% and is in agreement with the engineer's estimate. It is unfortunate that the isobaric ERD was not included in the first-pass design in lieu of the Pelton Wheel as the energy savings would have been substantially higher.

Although the energy savings with the ERDs is substantial, it is important to analyze the present worth costs to understand the payback period. Table 4.25 summarizes the present worth cost of energy and RO train equipment assuming an energy cost of $0.08 per kWh and a present worth duration of 25 years.

4.5.5 Lessons Learned

The Pelton Wheel was an appropriate ERD for use at the TBSDF at the time it was designed as it provides a lower cost of water produced than having no ERD. However, today's choice would clearly one of the isobaric ERDs, which deliver the lowest present worth cost.

Table 4.25. Present Worth Cost of First-Pass TBSDF

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) No ERD	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Pelton Wheel	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Isobaric ERD	Pelton Wheel Payback Period (years)
6%	0.91	0.74	0.69	0.7
3%	1.1	0.92	0.85	0.5
0%	1.5	1.2	1.1	0.4

4.6 Case Study #5: Perth Seawater Desalination Plant, Kwinana Beach, Australia

4.6.1 Basis of Selection

The Perth Seawater Desalination Plant (PSDP) in Kwinana Beach in Perth, Western Australia, was started up in November 2006. The SWRO plant has a total capacity of 38 mgd (144,000 m^3/d). At the time of commissioning, the PSDP was the biggest SWRO plant in the southern hemisphere and the largest water supplier for the city of Perth, supplying 17% of the city's demand. The main treatment objectives at the PSDP are to have TDS below 200 mg/L, maximum bromide concentration of 100 µg/L, and alkalinity as $CaCO_3$ higher than 50 mg/L.

During the design phase of the PSDP, the public demanded that the energy use be offset with renewable energy generation. Because the SWRO process is energy-intensive, the plant was an ideal candidate for several options. The joint venture responsible for the design and construction was instrumental in the development of a wind farm in Western Australia. The wind farm has a capacity of 80 megawatts (MW)—three times the maximum demand of the PSDP. In addition to this renewable energy plant, ERI's PX technology was implemented in the design to further reduce energy use at the plant.

4.6.1.1 Plant Description

The PSDP draws feed seawater from an intake in nearby Cockburn Sound, approximately 660 ft (200 m) offshore. Six pumps convey water through traveling screens. A total of 24 dual-media filter vessels and 14 5-µm cartridge filters are used as a pretreatment step before further treatment with a two-pass RO process. The plant is built in two identical halves, and one half can be operated while the other is off line for maintenance. Redundancy is built into the overall capacity for expected maintenance downtime.

The first pass consists of 12 SWRO trains and is fed with six split-case high-pressure centrifugal pumps. Each pump has a capacity of 5040 gpm (1144 m^3/hr) and is driven by 3490-hp (2600-kW) motors. The maximum efficiency of the pumps is 86%. Each first-pass train has 162 Protec 7M side-port pressure vessels with seven Filmtec SW30HR-LE400 membrane elements per vessel. The permeate from the first pass goes through further treatment in the second pass.

The second pass consists of six low-pressure BWRO trains with 104 vessels each. Each vessel houses seven BW30-LE440 membrane modules. Each pass has over 10% free space for expansion.

Treated water is stored in a 330,000-gal (12,500-m^3) onsite tank and transferred to Thompson Reservoir located 7.5 mi (12 km) east of the plant. The PSDP is installed with a sludge treatment facility.

The general PFD for the plant is presented in Figure 4.18.

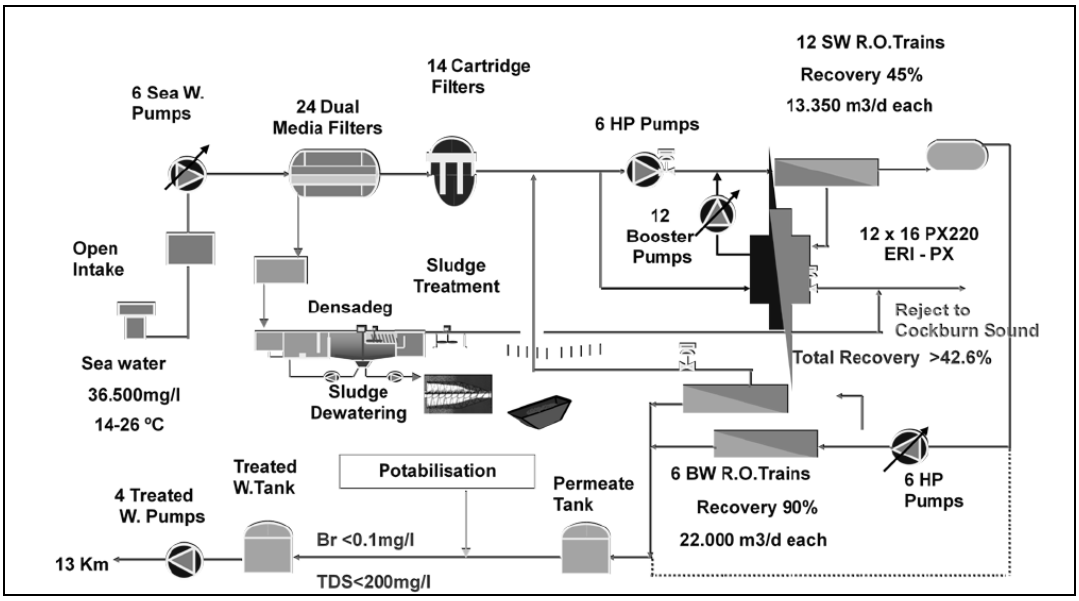

Figure 4.18. PSDP flow diagram.

The RO system schematic is presented in Figure 4.19.

Energy recovery is provided by 12 trains of 16 ERI Model PX-220 ERDs. Each train has a capacity of 3520 gpm (800 m^3/h). Figure 4.20 shows a flow diagram for the energy recovery setup at the PSDP.

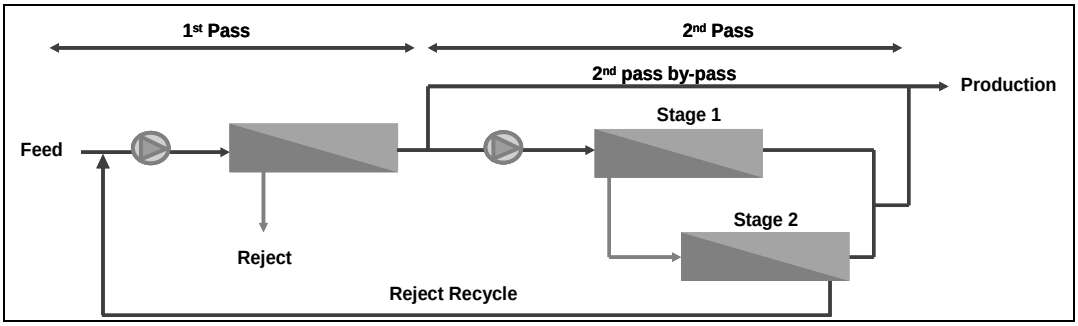

Figure 4.19. PSDP RO system schematic arrangement.

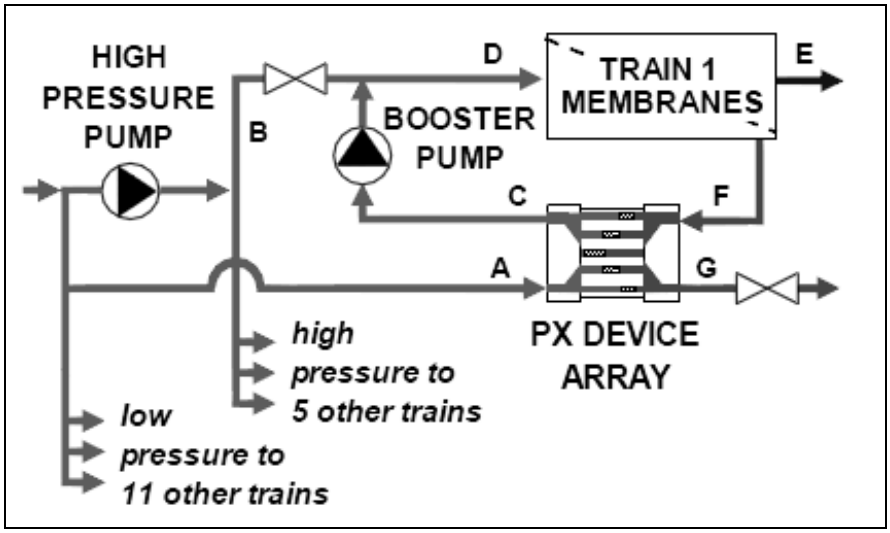

Figure 4.20. PSDP first-pass SWRO process and energy recovery schematic.

4.6.1.2 Desalination Plant Features

Table 4.26 summarizes the PSDP features.

Table 4.26. Desalination Plant Features

Parameter	Feature
Permeate capacity	38 mgd (144,000 m^3/d)
Design permeate recovery	45%—first pass 90%—second pass
Design feed TDS	36,000 – 37,100 mg/L
Design feed pressure	908 psi (6260 kPa)
Maximum differential pressure (first pass - second pass)	760 psi (5240 kPa)
Average permeate flux	7.76 gfd (13.2 lmh)—first pass 19.9 gfd (33.9 lmh)—second pass
Number of pressure vessels per train	162—first pass 104—second pass
Elements per pressure vessel	7
Total number of elements per train	1,134—first pass 728—second pass
Membrane element area, each	400 ft^2—first pass 440 ft^2—second pass
Element type	High-pressure SWRO (Filmtec SW30HR-LE400)—first pass Low-pressure BWRO (Filmtec BW30LE440)—second pass
Feed pump design point	5037 gpm (1,144 m^3/h) @ 908 psi (6260 kPa) TDH—first pass 4033 gpm (916 m^3/h) @ 145 psi (1000 kPa) TDH—second pass primary 4482 gpm (1018 m^3/h) @ 232 (1600 kPa) TDH—second pass secondary
Feed pump motor horsepower	2340 kW—first pass
Energy recovery device	Pressure exchanger—ERI PX 220

Table 4.27. Seawater Results Obtained by the Joint Venture during the Water Study and Pilot Plant Program

		Water Study		Pilot Plant
Analysis	**Units**	**1/07/2004**	**7/07/2004**	**7/12/2004**
Temperature	°C	18	17.6	23.5
pH	—	8.24	8.24	8.17
Conductivity	mS/cm	53.2	53.5	53.5
Sodium	mg/L	11,250	11,400	11,350
Potassium	mg/L	390	390	420
Calcium	mg/L	410	405	435
Magnesium	mg/L	1300	1355	1380
Boron	mg/L	4.9	4.9	4.7
Strontium	mg/L	8	7.7	8.4
Bromide	mg/L	67	68	62.5
Fluoride	mg/L	1.5	1.5	0.6
Chloride	mg/L	19,700	19,700	20,500
Sulfate	mg/L	2730	2760	2770
Bicarbonate	mg/L	152	154	160
TDS by summation	mg/L	36,013	36,246	37,091
Sum of major cations	meq/L	629.0	639.9	642.0
Sum of major anions	meq/L	615.2	615.9	638.6

4.6.1.3 Water Quality

A seawater testing program undertaken between June and August 2002 reported a variation in the TDS between 35,500 and 36,730 mg/L. The ionic composition was not reported.

Results of the seawater analyses carried out as part of the joint-venture pilot plant program conducted in 2004 are shown in Table 4.27.

The ionic breakdown used in the plant design is presented in Table 4.28.

Table 4.28. Feed Water Ionic Breakdown

Constituent	Units	Lower Salinity	Average Salinity	Higher Salinity	Finished Water Goal
pH	–	8.25	8.25	8.25	7.50–8.0
TDS	mg/L	36,000	36,500	37,100	<200
Calcium	mg/L	405	420	435	
Bromide	mg/L		67		<0.1
Boron	mg/L		4.7		<2.0
Magnesium	mg/L	1300	1340	1380	<0.02
Sodium	mg/L	11,090	11,190	11,335	
Chloride	mg/L	19,858	20,152	20,511	0.5–1
Sulfate	mg/L	2730	2750	2770	
Total hardness	mg/L as $CaCO_3$	6500	6600	6700	<10
Total alkalinity	mg/L as $CaCO_3$		152–160		<50

4.6.1.4 Chemical Use

The following chemicals are used in the PSDP treatment process:

- Sulfuric acid for pH correction of the pressure filter influent
- Ferric chloride, primary coagulant to pressure filter influent
- Coagulant aid for enhanced coagulation prior to the pressure filters
- Anti-scalant, Nalco PC1020, as scale inhibitor dosed to the RO feed
- Sodium hypochlorite for shock dosing of the intake pipeline
- Sodium metabisulfite to neutralize any residual chlorine in the seawater following shock dosing with sodium hypochlorite
- Lime and carbon dioxide to increase permeate calcium alkalinity and pH to stabilize the finished water
- Chlorine for primary and secondary disinfection of the RO permeate
- Fluorosilicic acid to provide for fluoridation of the finished water

4.6.2 ERD Evaluation and Selection

During plant design, the Pelton Wheel, DWEER, and PX ERDs were considered. No other ERDs were considered commercially and technically viable.

The PX ERD was chosen during design after a life-cycle cost analysis of the three ERD alternatives. It was believed that the initial capital cost would be offset by operating cost savings over a 20- to 25-year period because of the size of the plant. It was determined that the PX pressure exchangers would reduce the overall energy consumption by 60%, compared to 20% for a Pelton Wheel-type ERD.

There were several advantages and disadvantages associated with all of the systems. A Pelton Wheel must discharge at atmospheric pressure, which would require an open outlet channel

on the plant floor. Because of the location of the plant, further pumping would be required to discharge the brine.

The DWEER and PX devices transfer energy directly to the feed seawater by the use of a smaller booster pump. This would equate to a significant reduction in required power; however, both systems increase the salinity of the feed water because of cross contamination, resulting in a slight increase in energy use. On the other hand, neither device would require extra pumping of the discharge waste because of slight pressure in the line. Both devices also had 0.5 kWh/m^3 less power requirement than a Pelton Wheel.

In evaluating reliability for maintenance requirements, the DWEER technology was considered the least favorable because of all the moving parts and valves associated with the system.

The PX device was selected for use at the PSDP. A dedicated pressure exchanger train with 16 PX-220 devices was installed on each first-pass RO train. A dedicated booster pump also was installed after each pressure exchanger train to boost the RO feed pressure. The process schematic is presented in Figure 4.21.

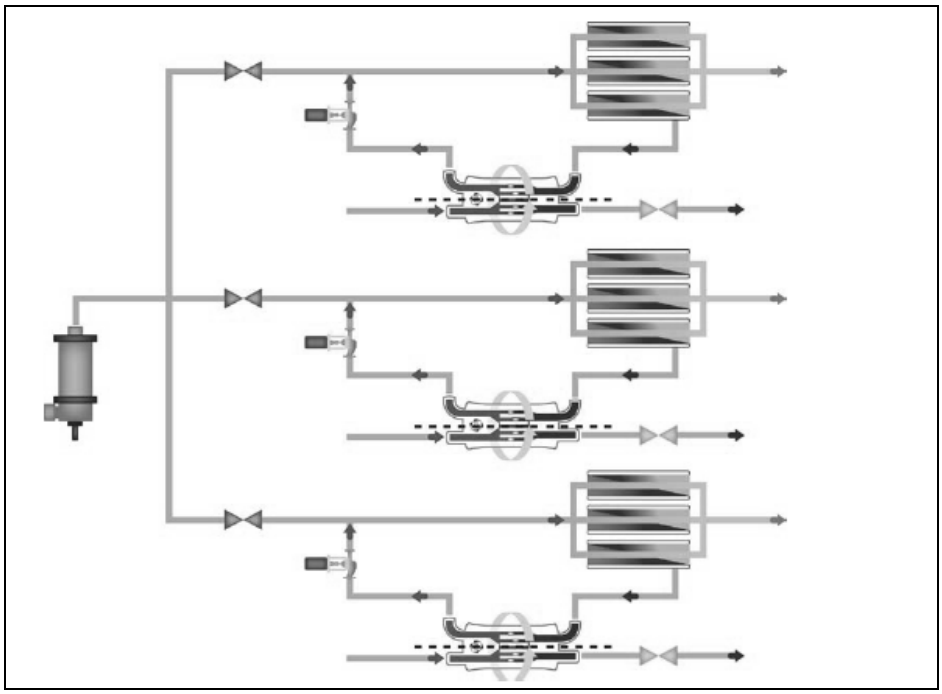

Figure 4.21. PSDP PX schematic.

The PSDP operational data indicate that the ERDs were 96% efficient. Feedback from the PX system's operation is positive.

The plant energy consumption ranges from 3.2 to 3.8 kWh/m^3, including intake and transfer into the distribution system. On the average, the SEC for the HPP is 2.40 kWh/m^3, and the energy consumption for the booster pump after the ERD is 0.07 kWh/m^3, bringing the total average SEC for the plant to 2.5 kWh/m^3.

A PX-220 train (16 PX-220 array) used at the PSDP has a maximum flow of 3520 gpm (800 m^3/h), but operates on an average flow of 2976 gpm (675 m^3/h). A photograph of one of the plant's 12 PX-220 trains, containing 16 PX-220 units operating in parallel, is presented in Figure 4.22.

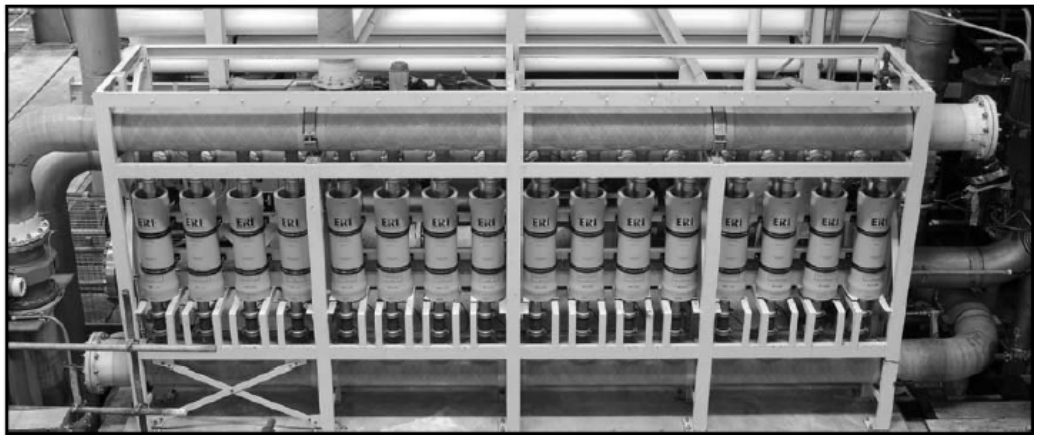

Figure 4.22. PSDP typical PX-220 train.

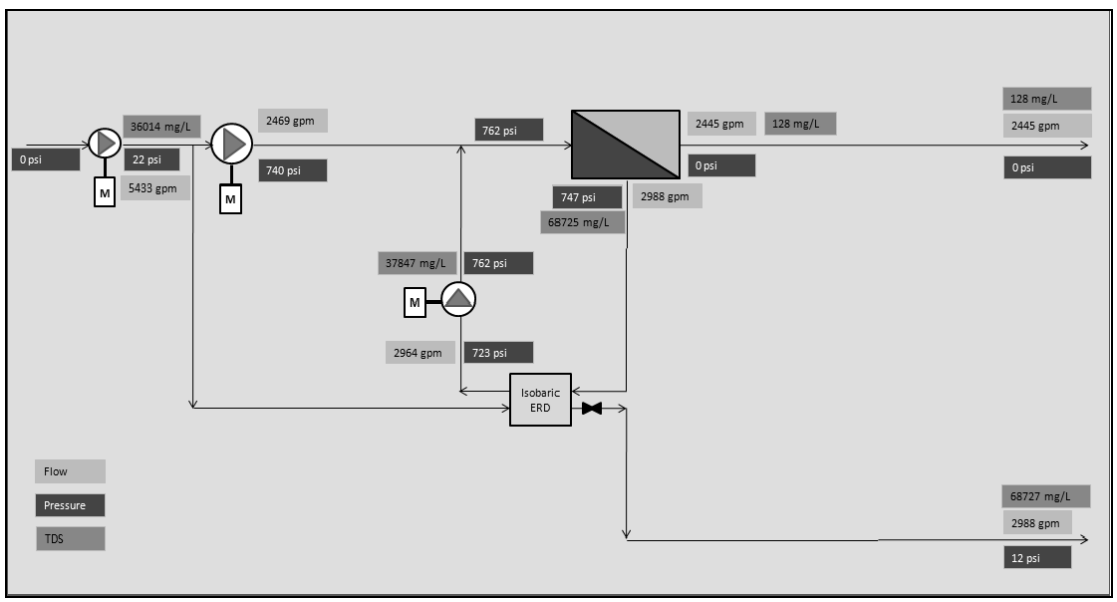

Figure 4.23. Model PFD of PSDP train.

Booster pumps for each RO train have a capacity of 2910 gpm (661 m^3/h) at 39 m of differential head, and are driven by 112-kW VFD controlled motors.

4.6.3 Modeling Simulation of Case Study

4.6.3.1 Results of Modeling Simulation

The tool provided the PFD shown in Figure 4.23 for a PSDP RO train incorporating the PX isobaric ERD.

4.6.3.2 Comparison on Model Simulation to Recorded Data

Based on the tool's calculations, the PSDP RO energy consumption with the PX ERD will be 7.7 kWh/1000 gal, or 2.0 kWh/m^3. This assumes that the RO high-pressure feed pump is operating at its maximum efficiency of 86%. Although 2.0 kWh/m^3 is substantially less than the 2.5 kWh/m^3 reported from Kwinana, the feed pumps at Kwinana are not dedicated per train. The plant uses a common feed pumping scheme, and individual RO train feed throttling valves control the feed pressure and permeate flow of each train. These valves will waste some energy, which possibly explains the difference.

4.6.4 Conclusion

The PX, DWEER, and Pelton Wheel ERDs were considered for the PSDP. Table 4.29 summarizes the predicted energy use of the RO system with each of these ERDs, as well as the system with no ERD. As with most SWRO systems, the introduction of an ERD will provide substantial energy savings. The tool predicts that the isobaric ERDs, namely the PX and the DWEER, will reduce the energy consumption by slightly over 50%. Although this is not quite the 60% assumed during the design phase, it is substantial nonetheless.

Table 4.29. PSDP Model Predictions

ERD	Predicted RO Energy Use (kWh/1,000 gal)	Predicted RO Energy Use (kWh/m^3)	Percent Energy Savings
None	15.0	4.0	N/A
DWEER	7.5	2.0	50
PX	7.7	2.0	49
Pelton Wheel	9.2	2.4	39

Table 4.30. PSDP Present Worth Comparisons for PX, DWEER, and Pelton Wheel

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) No ERD	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with ERI PX	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with DWEER	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Pelton Wheel
6%	0.95	0.63	0.62	0.70
3%	1.2	0.77	0.75	0.85
0%	1.6	1.0	0.96	1.1

Table 4.31. Present Worth and Payback Period

Discount Rate	ERI PX Payback Period (years)
6%	1.2
3%	0.77
0%	0.60

A reduction in SEC is the major benefit of incorporating an ERD into the RO system design, but the capital costs of adding the equipment need to be included in the analysis to determine the best ERD selection. This is achieved by analyzing the present worth costs of both RO equipment, including the necessary ERD equipment, and the energy use over the equipment life. Payback period and present worth cost of the RO equipment and energy use are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and the industry standard is 25 years. Assuming an energy cost of $0.08 per kWh and a present worth duration of 25 years, the tool estimates the present worth costs shown in Table 4.30.

Based on the tool's present worth calculations, either the DWEER or the PX is the most economical choice of ERD to implement. The present worth cost of the Pelton Wheel is substantially higher.

The energy savings associated with implementing the PX at the PSDP are estimated to be $815,000 per year per RO train. This results in a very rapid payback period for the ERD equipment, as shown in Table.31.

4.6.5 Lessons Learned

For SWRO, the payback period for the implementation of an ERD is quite short, as the energy savings are substantial compared to the capital cost investment of the ERD equipment. Furthermore, the isobaric ERDs, such as DWEER and PX, have efficiencies in excess of 95%, substantially higher than the Pelton Wheel, which has a maximum efficiency of about 90%. For this reason, the isobaric ERDs are being implemented on the majority of the larger SWRO systems today.

Chapter 5

Conclusion and Recommendations

5.1 Conclusions

5.1.1 Model Use

The goal of this project is to provide a useful planning tool to help utilities, regulators, engineers, and other stakeholders determine whether an ERD is appropriate (i.e., cost-effective) for a RO application and, if so, to select the most appropriate ERD for the specific application.

The tool is structured so that the common user can input basic system parameters through a single interface page and then select one or more ERDs for consideration. The tool then works through a series of calculations and outputs the results for each ERD selected. The advanced user can use the tool to compare various system parameters and their impact on ERD selection and costs. Although this tool will produce membrane projections, it is not intended to replace currently available projection software for RO manufacturers. Instead, the projections are estimates to support the ERD selection analysis.

The tool produces energy consumption comparison and costing information for various ERDs. These outputs are estimates to be used for preliminary planning purposes. Stakeholders should continue to work with engineers and vendors to obtain specific system quotes for ERD equipment.

5.1.2 ERD Selection for Inclusion in the Model

In developing the model, ERD products were included based on a number of criteria. First, only products that were commercially available at the time of model development were included. Second, the selected device had to have been installed in more than five applications.

Most municipal desalination plants are 0.2 mgd or greater capacity. Therefore, technologies currently available only in installations less than 100,000 gpd were eliminated from consideration. Certain ERDs, like the DWEER, have a minimum capacity unsuitable for small RO systems.

Last, devices where adequate cost or performance data were not provided by the manufacturer or were not readily available from the literature were not included in the model.

Tables 5.1 and 5.2 list decision matrices for the selected centrifugal and isobaric ERDs, respectively.

Table 5.1. Centrifugal ERD Selection Information

	High-Pressure Pump/Motor Type			Turbocharger Type	
Parameter	**Flowserve/ Calder Pelton Wheel**	**Deutching Pumpen Pelton Wheel**	**Francis Turbine***	**PEI**	**FEDCO**
Commercially available?	Yes	Yes	Yes	Yes	Yes
Adequate number of installations (>5)?	Yes	Yes	Yes	Yes	Yes
Capacity appropriate to municipal clients?	Yes	Yes	Yes	Yes	Yes
Adequate cost/ performance information provided or available?	Yes	No	No	Yes	Yes
Included in model?	Yes	No	No*	Yes	Yes

*The Francis turbine is no longer a popular option, as other ERDs have higher efficiency.

Table 5.2. Isobaric ERD Selection Information

Parameter	**PX**	**DWEER**	**SALTEC**	**RECUPER-ATOR**	**iSAVE**
Commercially available?	Yes	Yes	Yes	Yes	Yes
Adequate number of installations (>5)?	Yes	Yes	Yes	Yes	Yes
Capacity appropriate to municipal clients?	Yes	Yes	Yes	Yes	Yes
Adequate cost/performance information provided or available?	Yes	Yes	No	No	No
Included in model?	Yes	Yes	No	No	No

To summarize, the following ERDs were selected for incorporation into the tool:

1. Turbochargers:
   a. FEDCO HPB.
   b. ERI LPT, HALO, and HTC. The LPT is for applications lower than 570 psig; HALO and HTC are smaller- and larger-volume turbochargers, respectively, for higher-pressure applications.
2. Flowserve/Calder Pelton Wheel.
3. Isobaric devices.
   a. ERI PX
   b. Flowserve/Calder DWEER

As more information is made available on the devices listed in Tables 5.1 and 5.2 that were not included in the model, as well as on other devices that become commercially available, the tool should be expanded to include these devices.

Table 5.3. Expanded Present Worth Cost of First-Pass TBSDF

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Pelton Wheel	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Isobaric	Pelton Wheel Payback Period (years)	Isobaric Payback Period (years)
6%	0.68	0.62	1.2	**1.7**
3%	0.86	0.78	0.9	**1.3**
0%	1.2	1.0	0.6	**0.9**

5.1.3 Considerations for ERD Selection

5.1.3.1 Present Worth, Payback Period, ERD Efficiency

The decision on whether including an ERD in an RO system is economically worthwhile is based on the payback period. If the payback period is less than the projected equipment life, then ERD inclusion will save money over the duration of the equipment life.

However, ERD selection should be based on the present worth of equipment cost and energy, not on payback period or ERD efficiency. The tool returns both present worth project costs and payback period estimates. The ERD with the lowest present worth of the RO equipment and energy will have the lowest cost to the end user, regardless of the ERD efficiency or payback period. For example, in the Tampa Bay case study presented in Chapter 4, the isobaric ERD would have been a better choice than the Pelton Wheel, based on the present worth costs. The case study did not include the payback period for the isobaric system, which is presented in Table 5.3. The isobaric ERD would still have been a better option for Tampa Bay despite the fact that the payback period for the Pelton Wheel was shorter. The Pelton Wheel provides the lowest invested cost over the life of the project, whereas the payback period only determines how quickly the cost of the ERD will be recuperated.

The isobaric ERDs provide the highest efficiencies but are not always the best selection, particularly for brackish water or wastewater applications where multistage RO systems are used. The Bonita Springs case study showed that a turbocharger was the better choice, producing the lowest present worth cost despite the fact that the ERI PX had a much higher efficiency. On smaller BWRO systems such as the one used at Bonita Springs, the extra capital cost of the circulation pump and other auxiliary ERD equipment associated with the PX is not always outweighed by the better energy savings associated with the higher efficiency of the PX. The tradeoff between efficiency and initial capital cost needs to be reviewed on a case-by-case basis. In the case of Bonita Springs, the lower present worth for the HTC was influenced by ERD inclusion as a retrofit, where its use reduced the efficiency of the HPP. In a new application, the HPP would have been selected based on ERD use and its efficiency would have been maximized, thereby making the PX more attractive.

5.1.3.2 The Discount and Inflation Rates

The NPV power cost is used to compare future power costs against the initial capital cost in order to determine the payback period of the ERD. The NPV calculations are highly dependent on the discount and inflation rates inputted into the tool. Default values of 6% and

3%, respectively, are loaded into the tool, but the user is advised to find the rates that the client or utility has experienced in the past.

These rates have a significant impact on the NPV power cost calculated in the tool. At higher discount rates, the benefit of the energy cost savings is reduced in comparison to capital expenditures as future power costs become less costly in today's dollars. Thus, higher discount rates diminish the power savings of the ERD and increase the payback period. Higher inflation rates make future power costs higher, making the ERD more viable by decreasing the payback period.

5.1.3.3 Concentrate Backpressure

Backpressure applied to the concentrate discharge stream of the ERD will have an adverse impact on the energy recovered by a turbocharger or a Pelton Wheel. In southern California, for example, the RO desalting systems in the Inland Empire area discharge concentrate into a "Brine Line" formerly called the Santa Ana Regional Interceptor. This 93-mi gravity pipeline transmits nonreclaimable wastewater from the upper Santa Ana River basin to the ocean for disposal after treatment. The Inland Empire Brine Line is long, and the pressure in the line can be substantial.

In the case of the turbocharger, the pressure that is available to recover is equal to the concentrate pressure from the RO system minus the concentrate backpressure required to convey the concentrate to its discharge location. Thus, the higher the concentrate backpressure, the less energy can be recovered with a turbocharger. On the other hand, the PX isobaric system can handle substantial amounts of concentrate backpressure with little effect on energy recovery by the PX. For the PX, the low-pressure feed to the device needs to be approximately 10 psi higher than the concentrate effluent pressure; this additional feed pressure is typically available.

For example, if an Inland Empire desalination plant has an RO concentrate of 100 psig, and the Brine Line at that location has a backpressure of 25 psi, the net transfer efficiency (nte) of the turbocharger ERD—that is, the energy recovered by the device—would approximate nte × (100–25 psi), whereas the PX could recover approximately nte × 100 psi. This effect can be analyzed in the tool by increasing the concentrate pressure on the "Summary" page.

One of the disadvantages of a Pelton Wheel is that the concentrate exit flows freely from the device under atmospheric pressure (Wilf, 2004). If the water subsequently needs to be repressurized for disposal, this energy must come from a pump. The energy required for this pump must be subtracted from the energy recovered by the Pelton Wheel. The use of a secondary concentrate discharge pump for concentrate "repumping" is not included in the ERD.

5.1.3.4 SWRO and BWRO/Reclaimed Wastewater

As discussed in Chapter 2, most SWRO trains are single-stage, operate at recoveries in the range of 40% to 50%, and can have concentrate pressures as high as 960 psig. These characteristics are ideally suited to isobaric ERDs. At these high concentrate flows and pressures, the energy recovered through the ERD results in a rapid payback period. Any additional capital costs involved with incorporation of the ERD are minor compared with the significant energy savings available at these high pressures. The Kwinana, Australia case study demonstrated a payback period of less than 3 years for the ERI PX. In general, there is

a significant amount of energy available in the concentrate stream of a SWRO system, and ERDs, particularly the isobaric type, are ideally suited to capture and reuse this energy within the RO system, greatly reducing the system's energy consumption compared to that of one not using an ERD.

In contrast, the Luggage Point and Perris case studies for wastewater and BWRO systems, respectively, showed a payback period greater than 5 years for ERDs. This is an indication that the capital cost of the ERD equipment is significant in comparison to the energy that can be saved through ERD use. Furthermore, because these RO systems are designed with multistage trains, turbocharger use is favored (for interstage boost) despite reduced energy recovery efficiency compared with that achieved by an isobaric device.

5.1.4 Location of Turbocharger in a Multistage RO Train

Turbocharger capital cost is proportional to the boosted flow rate of the ERD. For this reason, the Luggage Point case study demonstrated that it was slightly more economical to place the turbocharger in front of the third stage rather than in front of the second stage of the RO train.

Furthermore, the location of the turbocharger can greatly affect the efficiency of the device. As discussed in Section 3.1.3.1, if the reject ratio of a system drops below 60%, the efficiency of the turbocharger is reduced. As a result, in a multistage RO train, it is better to place the turbocharger in a position to provide an interstage boost than to boost the feed pressure to the entire RO train.

5.1.5 ERD Retrofits for Existing Reverse Osmosis Plants

Evaluation of the existing RO operations is required when a plant is considered for an ERD retrofit. At a minimum, the high-pressure feed pump operation would need to be evaluated because a change in the pump's operating point (or range) may reduce the pump's hydraulic efficiency and counteract the energy savings benefit provided by ERD use. Depending on the mode of operation, the selected ERD will determine whether additional improvements are required at feed pumping.

5.1.5.1 Isobaric Energy Recovery Devices—Reduced High-Pressure Pump Capacity

The isobaric ERDs function by transferring energy from the RO concentrate to the portion of the feed stream that bypasses the HPP. If the RO train capacity is unchanged, the required capacity of the high-pressure RO feed pump will be decreased by the introduction of an isobaric ERD. A number of factors, including the recovery of the system, will affect the severity of this issue. For the Bonita Springs example, where the RO trains operate at 65% to 85% recovery, this resulted in the pump operating at a point where its efficiency was less than optimal. For a higher-pressure SWRO train, the capacity turndown would be on the order of 50%, and the pump may require replacement or a substantial amount of retrofitting. One way of working around this issue is to simultaneously increase the capacity of the RO train while installing the isobaric ERD.

5.1.5.2 Turbochargers—Reduced High-Pressure Pump Pressure

The turbocharger is a pressure-boosting device. If the RO train is single-stage, the turbocharger is placed in series with the high-pressure feed pump, reducing the required discharge pressure of the pump. The ratio of the turbocharger boost to the original pump

discharge pressure will determine the amount the discharge pressure is reduced. If the turbocharger is placed between stages in a multistage RO train, the high-pressure RO feed pump discharge pressure will be decreased by a smaller margin, but still needs to be investigated.

5.1.5.3 Pelton Wheel—Motor Replacement

Pelton Wheels are directly coupled to the HPP and motor shaft. A retrofit of an existing pump motor combination would require a motor replacement, at a minimum.

5.1.6 Energy Recovery Device Footprint

Turbochargers are offered in various different sizes geared toward matching the RO system concentrate flow with a single device. The footprint of the unit itself can vary from 1 to 9 ft^2, with piping requirements adding to this area. Figure 2.10 displays a turbocharger unit. Pelton wheels are sized to match the HPP. The isobaric ERDs, including the PX and DWEER, typically are configured with numerous units operating in parallel on a single RO train. The ERI units are stacked as in Figure 4.22 with the footprint getting larger as additional units are added. The DWEERs are typically stacked vertically and have the same footprint regardless of the number of units included. DWEERs are currently offered in two sizes with footprints of 5 ft $\times$ 30 ft and 5 ft $\times$ 25 ft, not including piping. In general, the isobaric ERD footprint is substantially larger than that required by a turbocharger. Each of these ERDs can be placed adjacent to the pressure vessels on the RO train.

In summary, the differences of the ERDs need to be considered. The user is encouraged to contact the ERD vendors to get details particular to their application.

5.2 Recommendations for Future Work

An annual review and update of the model is recommended. As evident in the literature review, the ERD market is expanding and evolving. As new technologies are brought to market and proved to be effective, the model should be updated to incorporate these technologies in order to remain relevant and of value to the WateReuse Research Foundation.

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Appendix A

Energy Recovery Device Summaries

A.1 Centrifugal Energy Recovery Device

Pelton Wheel/ERT		**www.flowserve.com**	
Name	Flowserve/Calder	Stock Symbol	FLS
Location	USA/Switzerland	Year Listed	1997
Founded	1790/1981	Annual Gross Revenue	$1.409 billion
Primary Market	Energy recovery in RO desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	Flowserve
Notes	Energy recovery turbine (ERT)		
Key Trademarks	None		

Products

Pelton Wheel

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
RO-350-70	66–660	15–150	≤86%
RO-350-100	250–1100	57–250	≤87%
RO-350-100-2	525–2200	119–500	≤88%
RO-350-100-4	1100–4400	250–1000	≤90%

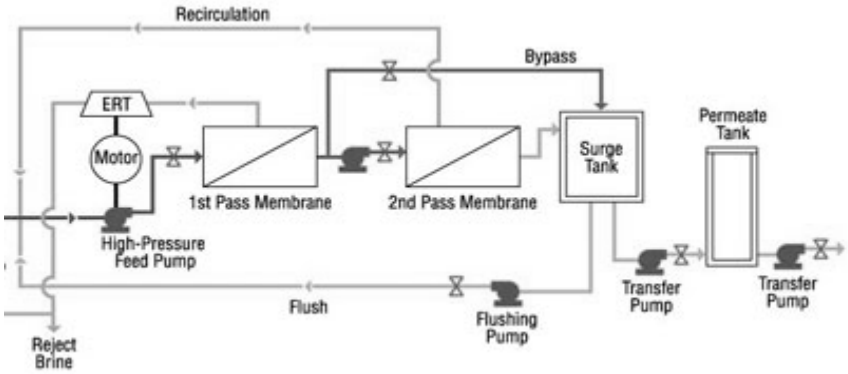
Process Description

The Pelton Wwheel is direct-coupled to the high-pressure pump (HPP) and motor shaft. Rotational energy from the concentrate is directly transferred to the motor shaft, reducing the power requirements. The HPPs for a direct-coupled device are sized for the full flow and pressure; however the motor power can be reduced as a result of the energy recovery.

In its operation, the high-pressure concentrate is fed into the Pelton wheel hydraulic impulse turbine, which then produces rotating power output to assist the main electric motor in driving the main HPP. The system consists of an adjustable input nozzle to convert water pressure into kinetic energy contained in a high velocity jet (Darwish et al., 2007). Energy recovery starts at about 40% of system pressure and the inlet nozzle acts as a brine control valve and no further pressure control is used on the RO system.

	Pelton Wheel/ERT	www.flowserve.com

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Las Palmas	Spain	45,000	11.9	Seawater
Trinidad	Trinidad	100,000	26.4	Seawater
Carboneras	Spain	140,000	37.0	Seawater
Tampa	USA	45,000	11.9	Seawater
Fujairah	UAE	180,000	47.6	Seawater

	Turbochargers		www.energy-recovery.inc
Name	Energy Recovery Inc.	Stock Symbol	n/a
Location	USA	Year Listed	n/a
Founded	1986 (PEI bought by ERI in 2009)	Annual Gross Revenue	n/a
Primary Market	Pumps and energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	ERI
Notes			
Key Trademarks	None		

Products

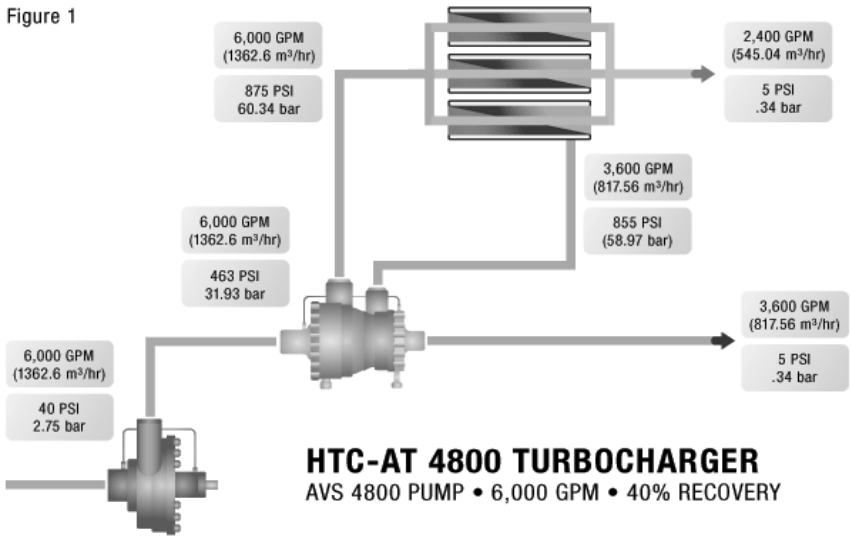
Turbochargers

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
LPT-32	25–55	6–12	49%
LPT-63	45–95	10–22	50%
LPT-125	70–185	16–42	52%
LPT-250	150–375	34–85	56%
LPT-500	300–750	68–170	62%
LPT-1000	600–1500	136–341	69%
LPT-2000	1000–2500	227–568	72%
LPT-4000	2300–4500	522–1022	72%
HALO-50	35–60	8–14	57%
HALO-75	60–85	14–19	57%
HALO-100	85–130	19–30	58%
HALO-150	130–180	30–41	60%
HALO-225	180–270	41–61	61%
HALO-300	270–350	61–80	63%
HALO-450	350–525	80–119	65%
HALO-600	600–900	136–204	68%
HALO-900	900–1300	204–295	69%
HALO-1200	1300–1500	295–341	70%
HTC-AT 1800	1500–2100	341–477	72%
HTC-AT 2400	2100–3000	477–681	73%
HTC-AT 3600	3000–4200	681–954	75%
HTC-AT 4800	4200–6000	954–1363	76%
HTC-AT 7200	6000–8400	1363–1908	78%
HTC-AT 9600	8400–12,000	1908–2726	80%

Process Description

In a turbocharger device, a Francis turbine is direct-coupled to pump impeller on a common shaft and located downstream of the HPP. The HPP is sized for the full-feed flow, but the head requirement is decreased by the boost provided in the turbocharger.

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
—	Algeria	500,000	132.1	AT-7200
—	UAE	113,000	29.9	AT-4800
—	UAE	45,000	11.9	AT-3600
—	India	45,000	11.9	AT-3600
—	Singapore	113,000	29.9	AT-2400
—	Thailand	15,000	4.0	AT-2400

HPB/HPB-HEMI		http://www.fedco-usa.com/	
Name	FEDCO	Stock Symbol	n/a
Location	USA	Year Listed	n/a
Founded	1997	Annual Gross Revenue	n/a
Primary Market	Pumps and energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	None

Notes: Low-pressure energy recovery for BWRO applications is supplied via separate pump and turbine modules. FEDCO custom designs and manufactures the turbine portion for specified brine flow and pressure ranges.

Key Trademarks: HPB, HEMI

Products

Turbochargers—High-Pressure

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
HPB 20	66–120	15–27	64%
HPB 30	100–167	23–38	66%
HPB 40	132–220	30–50	67%
HPB 60	200–330	45–75	71%
HPB 80	265–440	60–100	72%
HPB 120	400–660	91–150	73%
HPB 160	528–880	120–200	74%
HPB 250	825–1380	187–313	76%
HPB 350	1150–1930	261–438	77%
HPB 500	1650–2750	375–625	78%
HPB 700	2310–3850	525–874	79%
HPB 1000	3300–5500	750–1249	80%
HPB 1400	4620–7700	1049–1749	81%
HPB 2000	6600–11,000	1499–2498	82%
HPB 2800	9240–15,400	2099–3498	85%

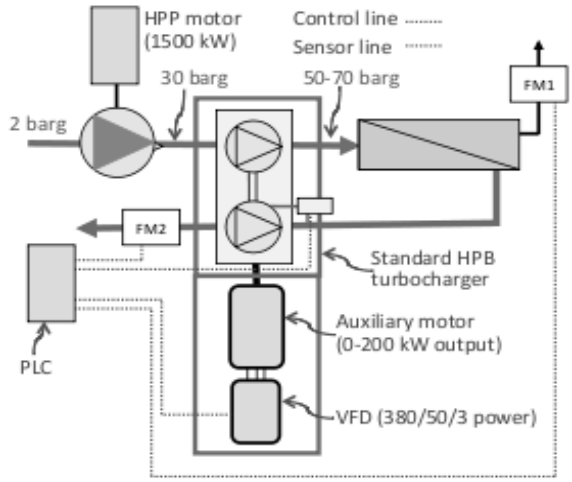
Turbochargers—Low-Pressure

LP HEMI	Custom-made for applications

Process Description: In a turbocharger device, a Francis turbine is direct-coupled to pump impeller on a common shaft and located downstream of the HPP. The HPP is sized for the full-feed flow, but the head requirement is decreased by the boost provided in the turbocharger.

HPB/HPB-HEMI	http://www.fedco-usa.com/

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
King Abdul Aziz International Airport Jeddah	Saudi Arabia	36,600	9.7	Seawater
Jeddah 3 (In Construction)	Saudi Arabia	260,000	68.7	Seawater
Turks & Caicos Water Authority	British West Indies	7,000	1.8	Seawater
NEWater—Changi plant	Singapore	240,000	63.4	Brackish
N. Lee County, FL	USA	47,000	12.4	Brackish
Adani, IOCL Paradeep	India	20,000	5.3	Seawater

A.2 Isobaric Energy Recovery Device

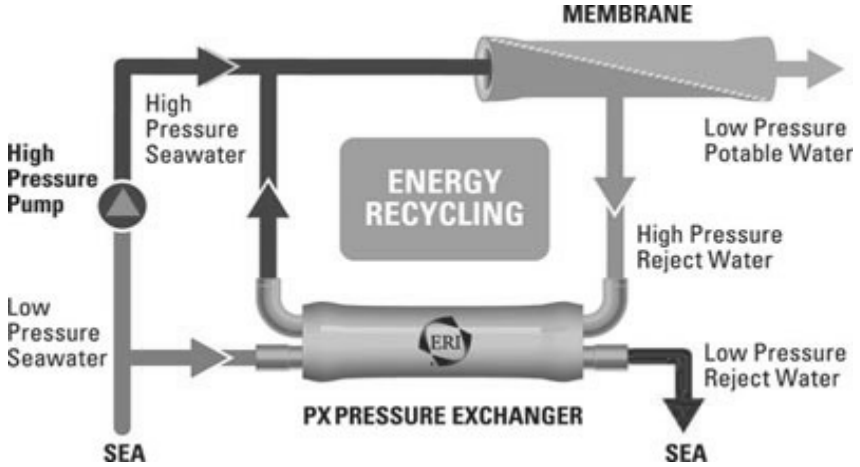
ENERGY RECOVERY INC.		http://www.energyrecovery.inc/	
Name	Energy Recovery Inc. (ERI)	Stock Symbol	ERII
Location	California, USA	Year Listed	2008
Founded	1997	Annual Gross Revenue	$50M
Primary Market	Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	Pump Engineering Inc.	Parent Company	Not applicable
Notes	ERI's proprietary rotary energy recovery device is called a PX pressure exchanger. ERI's marketing literature claims over 400 installations utilizing this technology, representing 70% of the current market share. Marketing literature also claims over 94% efficiency.		
Key Trademarks	PX (pressure exchanger)		
Products			

Isobaric Energy Recovery Devices

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
PX-300	200–300	45–68	96.8
PX-260	180–260	41–59	96.8
PX-220	140–220	32–50	96.8
PX-180	100–180	23–41	96.8
PX-140S	90–140	20–32	95.0
PX-90S	60–90	14–20	95.0
PX-70S	40–70	9–16	94.2
PX-45S	30–45	7–10	94.2
PX-30S	20–30	4.5–6.8	94.2

Circulation Pumps

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
VP-6891	1100–2200	250–500	75%
VP-4671	400–1100	91–250	80%
VP-3471	175–530	40–120	75%
HP-2402	130–230	30–52	59%
HP-2403	230–300	52–68	61%
HP-1253	100–160	23–36	68%
HP-1254	160–200	36–45	65%
HP-8503	50–70	11–16	70%
HP-8504	70–100	16–23	68%

	ENERGY RECOVERY INC.	http://www.energyrecovery.inc/
Process Description	In a PX device, high-pressure concentrate flows through the unit and transfers energy directly to a portion of the incoming lower pressure seawater feed (Stover, 2004). The heart of the device is a single cylindrical ceramic rotor that facilitates pressure exchanges. Ceramic was selected as the ideal material for this application because it is very tough, corrosion proof, and dimensionally stable. The rotor contains axial ducts arranged in a circle around a center tension rod (*Membrane Technology News Bulletin,* 2004). The rotor spins within a ceramic sleeve, and is enclosed on either end with dedicated feed and concentrate ceramic end covers. Bearing and sealing surfaces are the ceramic parts themselves, and bearing lubrication is provided by high-pressure feed water. The concentrate end cover contains a high-pressure (HP) concentrate port for incoming HP concentrate (HP IN), and a low-pressure (LP) concentrate port for outgoing concentrate (LP OUT). The feed water end cover likewise contains two feed water ports (LP IN and HP OUT). The PX device uses the high-pressure concentrate to directly pressurize feed water. The flow rate of concentrate is slightly greater than that of the feed water because a small amount of high-pressure feed water is used to lubricate the rotor. Therefore, the PX device provides the membranes the concentrate portion of the feed flow and the HPP provides the permeate portion of the feed flow and the small lubrication flow. In operation, a rotor duct is exposed to both the LP IN and LP OUT end cover ports. The LP feed water fills the rotor duct. The rotor duct then enters a Seal Zone where flow stops and the duct is sealed from the HP- and LP-flow circuits. Then the duct continues to rotate and is exposed to the incoming HP concentrate, which pressurizes the feed water and displaces it toward the membranes. The rotor then advances until the duct seals and the cycle begins again. The PX system is designed in way that the feed water and concentrate come into direct contact in the rotor, with minimal mixing of the streams within the duct. Mixing increases the feed water TDS, requiring slightly higher feed pressures to maintain the desired flux and recovery.	
Process Schematic		

ENERGY RECOVERY INC.				http://www.energyrecovery.inc/	
Key Installations	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
	Hadera Desalination plant	Israel	388,000–462,000	102.5–122	Seawater
	Torrevieja	Spain	240,000	63.4	Seawater
	Tenes Desalination Algeria	Algeria	200,000	52.8	Seawater
	Barcelona	Spain	200,000	52.8	Seawater
	Hamma	Algeria	200,000	52.8	Seawater
	Kwinana Seawater Desalination Plant	Australia	160,000	42.3	Seawater
	Southern Seawater Desalination Plant	Australia	100,000	26.4	Seawater
	Port Stanvac	Australia	135,000	35.7	Seawater
Comments	PX devices are also available with lower pressure ratings for brackish water applications.				

	DWEER		www.flowserve.com
Name	Flowserve/Calder	Stock Symbol	FLS
Location	USA/Switzerland	Year Listed	1997
Founded	1790/1981 Flowserve purchased Calder in 2009	Annual Gross Revenue	$1.409 billion
Primary Market	Energy recovery in RO desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	Flowserve
Notes			
Key Trademarks	DWEER		
Products			

Isobaric Energy Recovery Devices

Name	Capacity (m^3/d)	Capacity (mgd)	Efficiency	Mixing
"A"; D-1550	790–1550	179–352	98%	<2.5%
"B"; D-1050	440–1100	100–250	98%	<2.5%

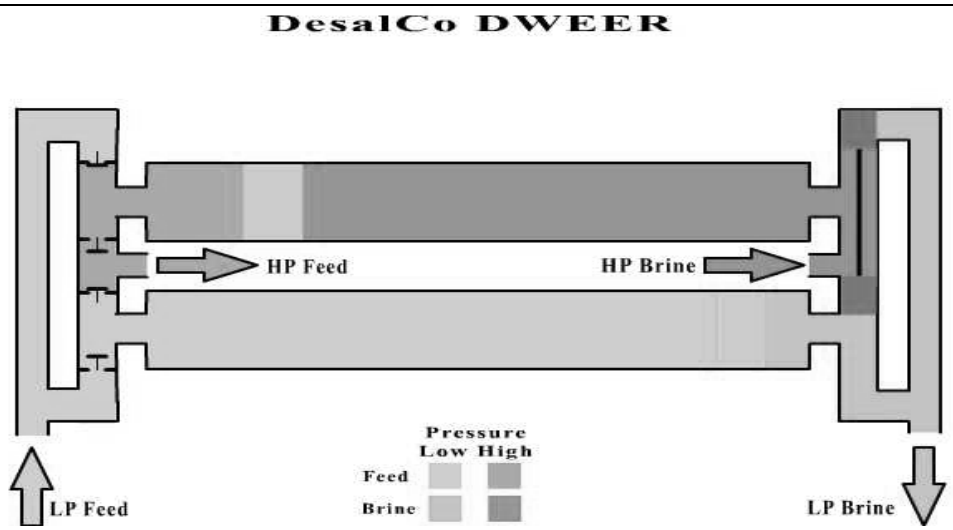
	DWEER	www.flowserve.com

Process Description

The DWEER uses positive displacement pistons, which are normally housed within pressure vessels to sequence energy recovery (Andrews et al., 2001). The DWEER work exchanger is designed with a minimum of two pressure vessels in parallel. In its operation, DWEER transfers the fluid pressure in the brine stream to fluid pressure in the feed across a piston, where it reduces mixing of the brine and feed. One vessel is in the working stroke while the other is filled with fresh seawater. As soon as the piston of the working pressure vessel finishes its working stroke and the filling vessel is fully filled with fresh feed water, the brine and feed line are switched (Schneider, 2005). If the piston is designed for minimum drag, the transfer of energy in this scheme is essentially 100%. For this reason, the fundamental exchange of energy between the brine and seawater feed is more efficient than centrifugal devices relying on shaft conversion of power (Farooque et al., 2004).

It is important to note that in an actual RO system, there is a pressure drop between the feed entering the RO module and the brine exiting from it and entering the DWEER. Because of this loss, it is not possible for the effluent from the DWEER to flow back into the feed. The pressure vessel has a limited volume, so a valve causes the two vessels to exchange functions before the piston in that volume completes its stroke. By installing a booster pump, flow and pressure equilibrium conditions are established. Typically such a pump is designed for a differential head of about 30 to 40 m (Schneider et al., 2005). The flow exiting the DWEER is now able to match the discharge pressure of the HPP (which has a capacity equivalent to the permeate flow), and hence allowing the system to operate in a loop (Farooque et al., 2004).

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Grand Cayman	Cayman Islands	4,900	1.3	Seawater
Ashkelon	Israel	330,000	87.2	Seawater
Tuas	Singapore	110,000	29.1	Seawater

Recuperator		www.aqualyng.com	
Name	Aqualyng	Stock Symbol	n/a
Location	Norway	Year Listed	n/a
Founded	1992	Annual Gross Revenue	Not Reported
Primary Market	Reverse osmosis systems	Secondary Market	None
Subsidiaries	None	Parent Company	Aqualyng AS

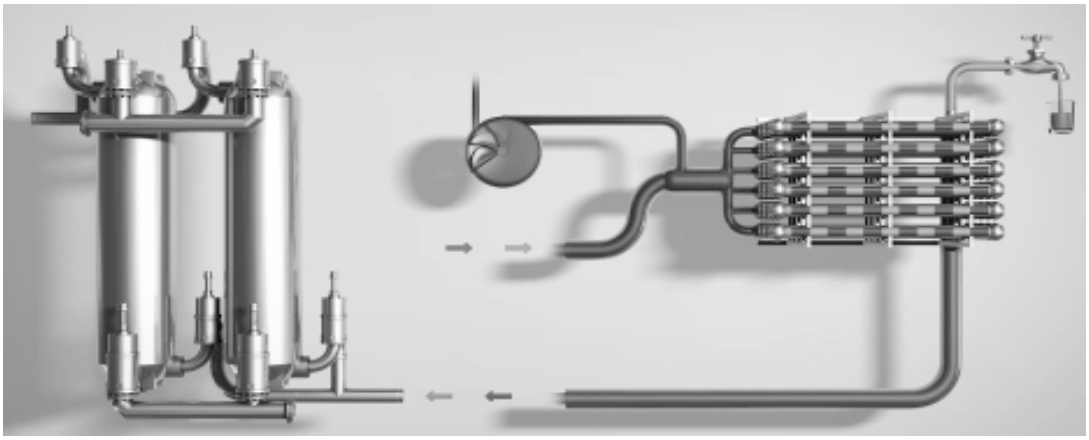
Notes: The Aqualyng Recuperator is not offered for sale as a standalone product, but is instead supplied as a proprietary energy recovery device in an Aqualyng desalination system.

Key Trademarks: Recuperator

Products (TYPE)

Name	Capacity (m^3/d)	Capacity (mgd)
RO-500STD	92	21
RO-1000STD	183	42
RO-2000STD	367	83
RO-5000STD	917	208
RO-10000STD	1835	417

Process Description: In its operation, the Recuperator uses the saline reject in a sequential process to directly pressurize seawater in two upright pressure exchange vessels (Drablos et al. 2002). The process is designed to achieve the same flow and pressure as the saline reject without mixing of respective fluids. To compensate for the pressure drop across the membranes (0.5–1.5 bar) and in the recuperator system (0.2–0.6 bar), the system is fitted with a booster pump. The system is highly automated without interruptions in flow of high-pressure seawater to the membranes.

	Recuperator				www.aqualyng.com
Process Schematic					
Key Installations	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
	Caofeidian	China	50,000	13.2	Seawater

Clark Pump		http://www.spectrawatermakers.com/	
Name	Spectra Watermakers Inc.	Stock Symbol	n/a
Location	California	Year Listed	n/a
Founded	1997	Annual Gross Revenue	n/a
Primary Market	Small capacity RO energy recovery devices	Secondary Market	None
Subsidiaries	n/a	Parent Company	n/a

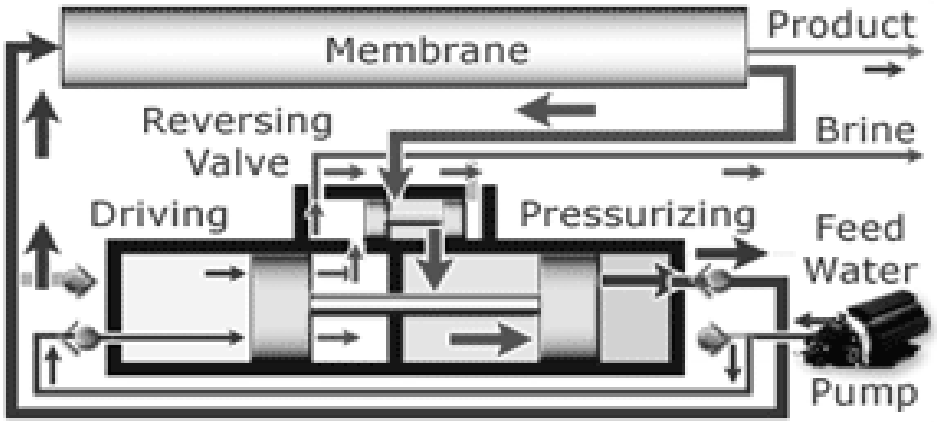
Notes: Spectra Watermakers is privately held U.S.-based company specializing in the supply of compact desalination devices for the marine industry. The Clark Pump is a highly efficient, low-flow device utilized in small package systems. The prime market for systems of this size include yachting desalination systems and autonomous renewable energy powered systems.

Key Trademarks: None

Products

Process Description: The Clark Pump is a single-vessel, two-chamber, isobaric energy recovery device. Similar to larger isobaric, multichamber ERDs, an external pilot valve (reversing valve) controls the sequencing and flow of water through the device. The system is designed for a fixed recovery depending on the area displaced by the shaft on the concentrate side of the piston.

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Numerous small installations	Global			

Comments: Although the Clark Pump is applicable to low-capacity applications, it is not applicable at this time for larger installations.

	Pearson Pump		http://www.spectrawatermakers.com/
Name	Spectrawater Makers	Stock Symbol	n/a
Location	California	Year Listed	n/a
Founded	Not reported	Annual Gross Revenue	n/a
Primary Market	Small capacity RO energy recovery devices	Secondary Market	None
Subsidiaries	n/a	Parent Company	n/a

Notes: Spectra Watermakers is privately held US based company specializing in the supply of compact desalination devices for the marine industry. The Pearson Pump is a highly efficiency, low-flow device utilized in small package systems. The prime market for systems of this size includes yachting desalination systems and autonomous renewable energy powered systems.

Key Trademarks: None

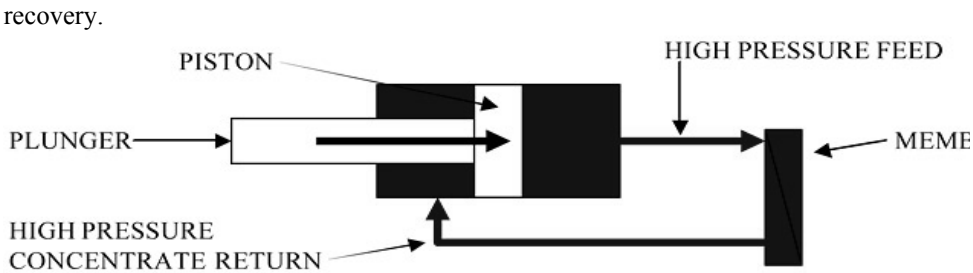
Products

(TYPE)

Name	Capacity (m^3/d)	Capacity (mgd)	Recovery	Efficiency
Pearson Pump	3.5–6.5	0.8–1.5	20% 30% 50%	≤80%

Process Description: The Pearson Pump is a positive displacement three cylinder reciprocating HPP with the same motors and crankcases used in conventional RO system feed pumps. The Pearson Pump head delivers water to the membranes in the same way as conventional feed pumps but is capable of recovering the energy in the concentrate. This is done by returning the concentrate to the Pearson Pump at high pressure, where it flows into the pump cylinders on the undersides of the pistons, transferring its energy to the feed water being discharged to the membranes. The energy recovered from the concentrate reduces the load on the pump motor, reducing the electrical consumption dramatically. Like other similar devices (such as Vari-RO), the Pearson pump operates at a fixed recovery. The device is available in multiple designs ranging in recovery from 20% to 50% recovery.

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Numerous small installations	Global			

	iSAVE		http://www.isave.danfoss.com
Name	Danfoss	Stock Symbol	n/a
Location	Denmark	Year Listed	n/a
Founded	1933	Annual Gross Revenue	31,550m DKK
Primary Market	Energy Recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	n/a

Notes

The iSave energy recovery device couples an isobaric ERD and booster pump into a single system, eliminating a unit process in the implementation of seawater desalination. They are targeted at individual trains of less than 4,000 m^3/d. Although sales figures for the iSave are not available, over 15,000 pumps were reported sold in 2009.

Key Trademarks

iSAVE

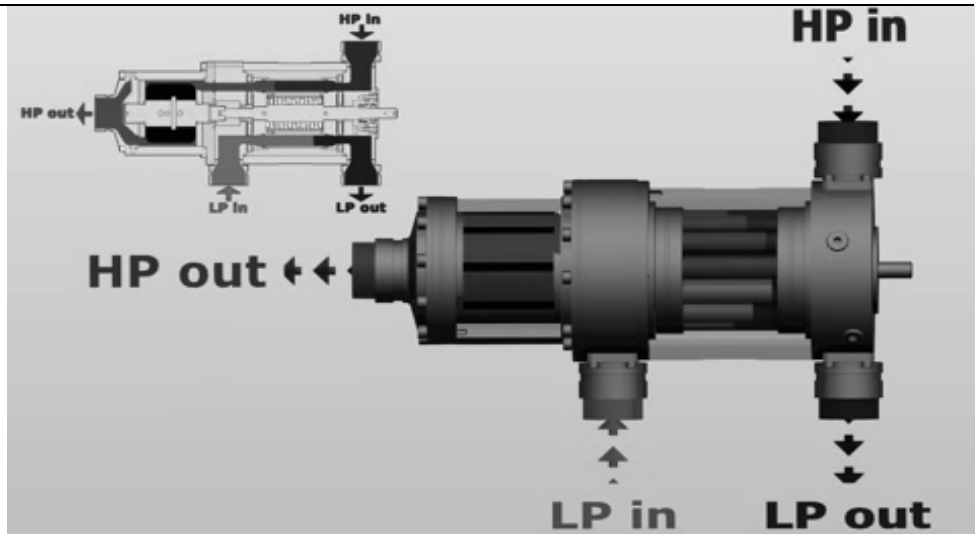
Products

iSave Integrated Pump and Energy Recovery System

Name	Capacity (m^3/d)	Capacity (mgd)	Efficiency
iSave 21	62–92	14–21	Up to 93%
iSave 40	97–176	22–40	Up to 93%
iSave 60	172–264	39–60	Up to 94%
iSave 77	260–339	59–77	Up to 95%

Process Description

The iSave consists of an isobaric pressure exchanger (PE), a high-pressure positive displacement booster pump (BP), and an electric motor coupled into a single package. The technology utilized in the isobaric exchangers is based upon technology used in the Danfoss APP pumps, and the high-pressure booster pumps are based on the vane pump principle enabling a very light and compact design. The iSave is a self-lubricating device and is constructed of stainless steel, duplex or super-duplex depending upon the application. The vane pumps are fixed displacement pumps in which the flow is proportional to the number of revolutions of the driving shaft enabling flow control. The electric motor provides speed control of both the pressure exchanger and the high-pressure booster pump on the same shaft—preventing over spin / over flushing. A VFD controlling the speed of the iSave also provides fail-safe communication to the service staff. Current applications for the iSave device include marine and container based installations.

	iSAVE				http://www.isave.danfoss.com
Process Schematic					
Key Installations	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
	Numerous small installations	Global			
Comments	Like many other ERDs, the salinity of the feed is increased as a result of leakage within the device. Typical leakage increases the salinity on the order of 2%–5% of the feed water salinity, depending on RO recovery and unit flow rates.				

SALTEC		www.ksb.com	
Name	KSB	Stock Symbol	KSBG
Location	Germany	Year Listed	1895
Founded	1871	Annual Gross Revenue	>€1,900M
Primary Market	Pumps and Energy Recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	None

Notes: SalTec ERD developed in 2004

Key Trademarks: SalTec

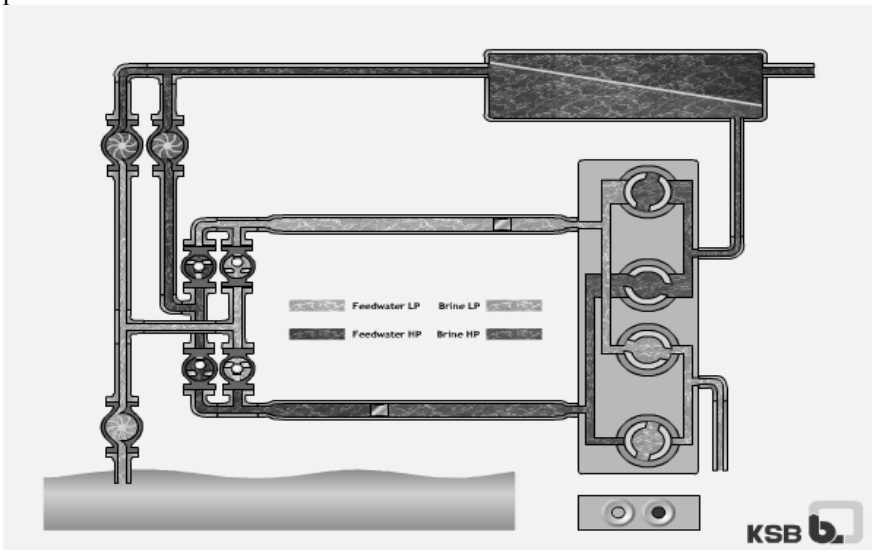
Products

Isobaric Energy Recovery Devices

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency	Mixing
DT160	704	160	Not Reported	<1%
DT250	1101	250	Not Reported	<1%

Process Description: SalTec N System includes a HPP, pressure exchanger, and booster pump. Noise produced is less than 80 dB.

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Pembrook (2008)	Malta	40,000	10.6	Seawater
Sharm El Shiekh (2004)	Egypt	1,920	0.51	Seawater

	IPER		n/a
Name	Vari-RO Inc.	Stock Symbol	n/a
Location	California	Year Listed	n/a
Founded	2003 (Bought by GE in 2011)	Annual Gross Revenue	n/a
Primary Market	Pumps and Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	GE

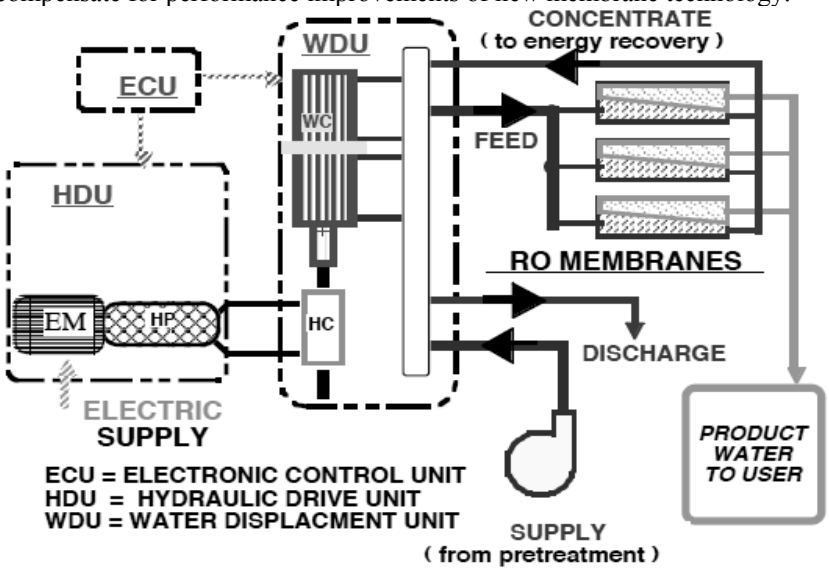
Notes: Currently, Vari-RO has no full-scale operating installations.

Key Trademarks: Vari-RO, IPER

Products: Not commercially available

Process Description: This positive displacement ERD system is suitable for large capacity RO desalting facilities. It has three double acting pistons that operate in complementary fashion to provide smooth, low pulsation discharge flow.
The variable flow feature of the VARI-RO technology allows the system to be started unloaded and gradually brought up to design flow conditions. Also, the flow and pressure can be adjusted during operation to optimize system performance; or to compensate for performance improvements of new membrane technology.

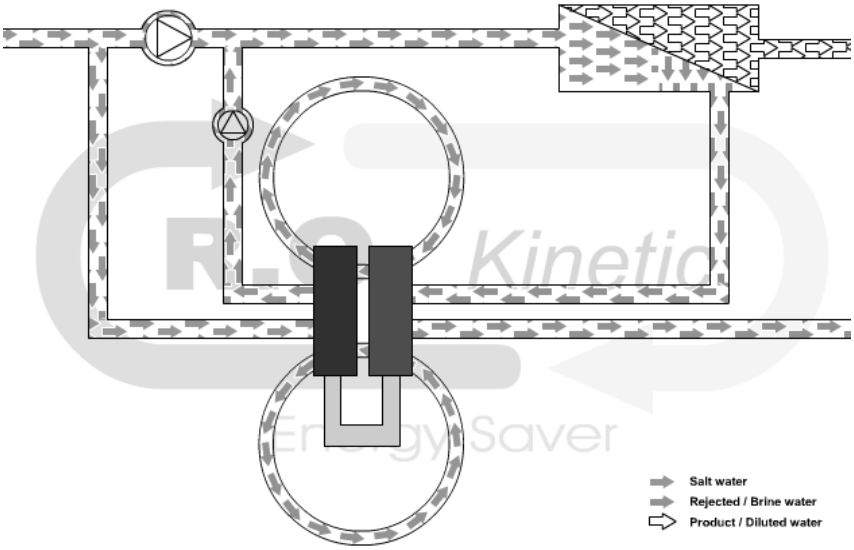
Process Schematic:



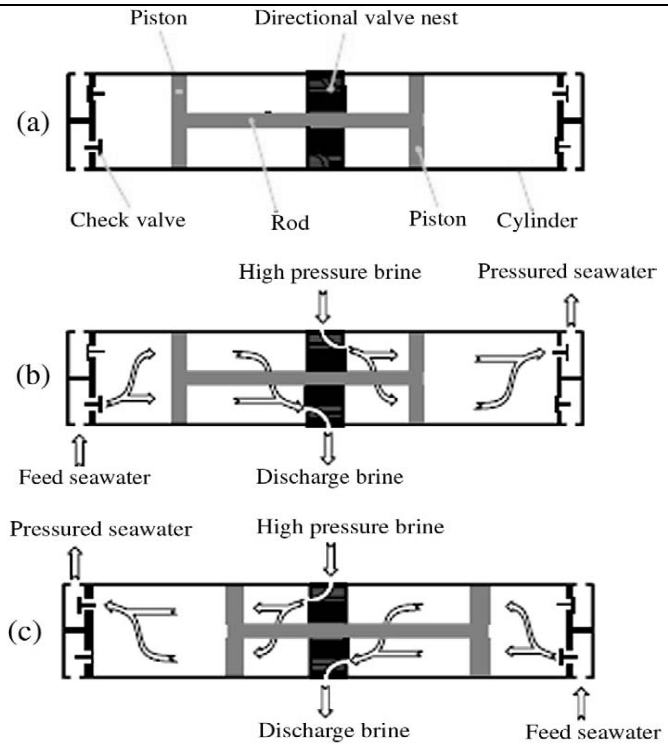
Key Installations:

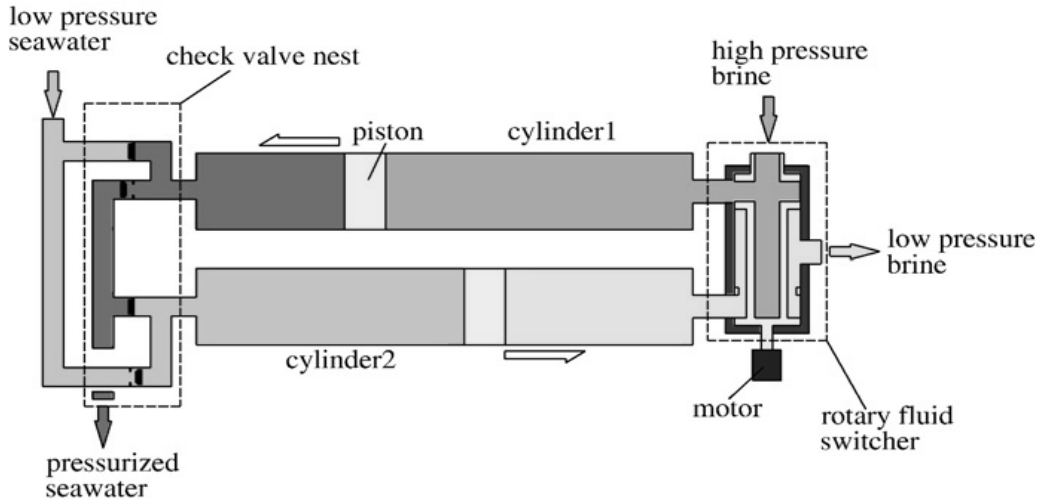
Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Catalina Island SWRO	California	SWRO (in construction)		

RO-KINETIC		n/a	
Name	RO Kinetic	Stock Symbol	n/a
Location	Canary Islands	Year Listed	n/a
Founded	n/a	Annual Gross Revenue	Not Reported.
Primary Market	Pumps and Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	None
Notes	Developing ERD device		
Key Trademarks	RO Kinetic		
Products	Proprietary desalination system/ERD		
Process Description	RO Kinetic pressure exchangers are designed in the form of a ring or closed loop. The water entering or leaving must be pressurized or depressurized, and is always in continual motion to avoid unnecessary consumption of kinetic energy from stops in the operation. Furthermore, the device is designed so that the ratio between length and diameter reduces the chances of excessive pressure drops or mixing (Peñate et al., 2010). The system housing consists of two bodies of servo-controlled valves, separated by two inertia valves. The banks of valves distribute input of seawater and output of brine from the pressure exchangers sequentially. The design of these valves prevent cavitations, turbulence or excessive pressure drops. The inertia valves are an extension to the pressure exchangers. To avoid the water shocks that may occur during the small stop that takes place during the valve operation while the chambers are filling up, the RO Kinetic® installation is also equipped with an expansion bladder in order to act as a water hammer damper (Peñate et al., 2010). In its operation, the passage of the water from one chamber to another is done with practically no interruption, because of the speed with which valves are activated. The feed water accumulated in one of the pressure exchangers is pressurized with a HPP. This step is accomplished by making a closed circuit between the membrane output and the reverse osmosis (RO) module input, where a water tank (pressure exchanger) and a booster pump are fitted into the line. The brine output from the RO rack and the seawater input to the membranes are at the same static pressure, supplied by the HPP. The brine is then fed into the pressure exchanger and displaces the feed water contained in the chamber, forcing it into the module input. To achieve this, the pressure differential (ΔP) caused by pressure drops (1 to 2 bars) that take place in the membranes and in the pressure exchangers must be overcome. Hence, the booster pump is designed to overcome this pressure drop of about 3 bars. It is reported that the system can achieve a maximum energy efficiency of approximately 98%. It is reported that this system is the only system in the world that takes maximum advantage of the kinetic energy, working in a continuous kinetic cycle (Dpto. Técnico Tecnovalia, 2006). This process can reach SEC levels of 2.10 kWh/m^3 (for a SWRO plant with a nominal production capacity of 2000 m^3/day), compared with 3.50 to 4.00 kWh/m^3 in optimized facilities turbine-type energy recovery devices. The reduction of the SEC is between 25 and 50% compared to plants with conventional ERDs. This reduction, of practically 50% of the variable costs in the desalination plant, represents a reduction of 25% of the total cost (Peñate et al., 2010).		

	RO-KINETIC	n/a			
Process Schematic					
Key Installations	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
	El Fraile	Canary Islands	1800	0.48	Seawater
	El Confital	Canary Islands	4000	1.06	Seawater
	Arona Hotel	Canary Islands	200	0.05	Seawater
	Aguas de Ponta Preta	Cape Verde	1000	0.26	Seawater
	Aguas de Ponta Preta	Cape Verde	1000	0.26	Seawater
	Aguas de Porto Novo	Cape Verde	500	0.13	Seawater
Comments	Model #s: K-200, K-1000				

Hydraulic Energy Recovery (HER)		www.tju.edu.cn/	
Name	HER	Stock Symbol	n/a
Location	China	Year Listed	n/a
Founded	Not reported	Annual Gross Revenue	n/a
Primary Market	Small-capacity RO energy recovery devices	Secondary Market	None
Subsidiaries	n/a	Parent Company	n/a
Notes	HER has not yet been produced on a commercial scale. However, the simulation work indicates that the HER device has a promising application in small-scale SWRO system.		
Key Trademarks	HER		
Products	Not commercially available		
Process Description	The HER device recovers the hydraulic energy from the high-pressure brine steam and returns it directly to the feed seawater. The two pistons are connected by a central rod and are assembled in two cylinders, respectively. The middle locator of the two cylinders is the directional valve nest, which achieves the switch of flow direction of high-pressure brine and discharge brine. The four check valves are installed at the end of the cylinders. The feed and the high-pressure brine both act to push the pistons to move, thus driving the pressured seawater. When one piston reaches the front of the directional valve nest, it pushes the directional valves to the next station, after that the moving direction of the pistons are reversed, as shown in Fig. c, and the piston travels back to the left, until it again reverses. Directional valves timing is critical to minimize pressure surges and avoid the water hammer caused by the change of flows in the cylinders. For this reason, four check valves are used and accumulators should be installed in SWRO system. Unlike the Clark pump (Thomas et al., 2002) and the Pressure exchanger–intensifier (Folley et al., 2008), directional valves of the HER device are installed inside and are driven by the pistons. Because the switches of the directional valves belong to an instantaneous process, the pressure surges during the switches can be effectively weakened or even eliminated (Sun et al., 2008). The device has a high-pressure transfer efficiency of approximately 94%. The simulated results show that the HER device can decrease the SEC of the SWRO system from 10 kWh/m^3 to 3.0 kWh/m^3. The pressure transfer efficiency of the HER device is approximately 94%.		

Hydraulic Energy Recovery (HER)	www.tju.edu.cn/
Process Schematic	
Key Installations	None

	FS-ERD		n/a
Name	FS-ERD	Stock Symbol	n/a
Location	China	Year Listed	n/a
Founded	n/a	Annual Gross Revenue	n/a
Primary Market	Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	n/a
Notes	Chinese research institution		
Key Trademarks	FS-ERD		
Products	Not commercially available		
Process Description	The FS-ERD is mainly composed of three parts: a rotary fluid switcher, two pressure cylinders, and a check valve nest. The core component of the FS-ERD is the rotary fluid switcher, which has four joint ports and two working phases similar to a two position four-way valve. A piston is installed in each cylinder to isolate seawater from brine and ensure minimum mixing between them during the operation. The position of the piston is detected to judge whether the pressurizing or depressurizing stroke has been accomplished, and when the fluid switcher should be changed to the next working phase. In the first phase, the HP brine stream is imported into cylinder 1 and therein the pre-filled low-pressure (LP) seawater feed is pressurized and pumped out, which is called the pressurizing stroke. Simultaneously, the HP brine stream in cylinder 2 would be depressurized and drained out by the incoming LP seawater feed, which is called the depressurizing stroke. Thereafter, when the FS-ERD accomplishes its pressurizing stroke (and also the depressurizing stroke), the switcher would rotate to working in the second phase at a low speed of 7.5 rpm driven by motor, which denotes that the stroke modes in cylinders are alternated to each other (Wang et al., 2010). No known sizable installations exist to date, FS-ERD and has not yet been produced on a commercial scale. However, the demonstration of parallel FS-ERDs under a real SWRO operating pressure is in progress at the FS-ERD test stand with a capacity of 2×500 m^3/d in our laboratory (Wang et al., 2010).		
Process Schematic			
Key Installations	None		

Appendix B

Validation of CH2M HILL Tool

B.1 Projection Validation. Bonita Springs

B.1.1 Bonita—Hydranautics IMS Design

Table B.1. Bonita Hydranautics Comparison

			IMS Design			CH2M HILL			%
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Change in Feed Pres.
1	ESPA2	14.9	227.6	55.2	61.6	214.4	30.7	57.8	-6%
2	ESPA2	16.7	245.8	48.5	73.1	233.3	28.3	68.8	-5%
3	ESPA2	12.8	205.5	50.9	11.4	194.8	40.0	44.9	-5%
4	CPA5-LD	14.9	244.1	43.0	31.5	238.1	19.7	38.5	-2%
5	CPA5-LD	16.7	265.1	37.9	37.1	260.6	17.7	46.0	-2%
6	CPA5-LD	12.8	219.7	50.9	25.6	214.6	24.1	30.1	-2%

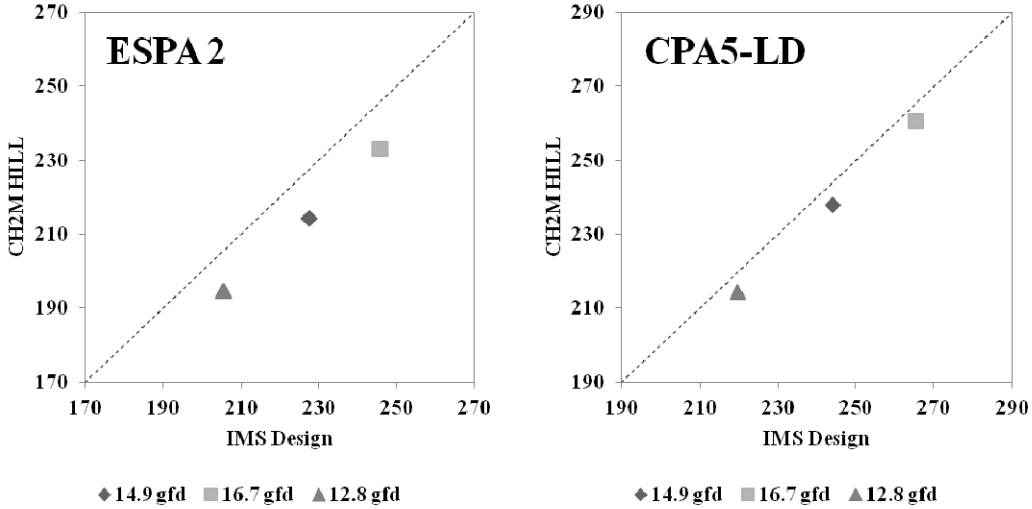


Figure B.1. Bonita Hydranautics Feed Pressure (psi)

B.1.2 Bonita—DOW ROSA

Table B.2. Bonita DOW Comparison

			ROSA			CH2M HILL			%
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Change in Feed Pres.
1	LE-400	14.9	221.14	52.4	72.3	191.54	97.8	49.2	-13%
2	LE-400	16.7	239.18	46.5	85.15	207.50	95.5	58.4	-13%
3	LE-400	12.8	199.48	61.3	58.8	176.86	147.1	37.8	-11%
4	BW30-440i	13.5	267.69	33.5	71.76	240.69	37.4	55.5	-10%
5	BW30-440i	15.2	293.34	29.9	84.12	263.20	33.8	66.2	-10%
6	BW30-440i	11.6	237.76	39.1	58.66	216.37	46.1	43.4	-9%

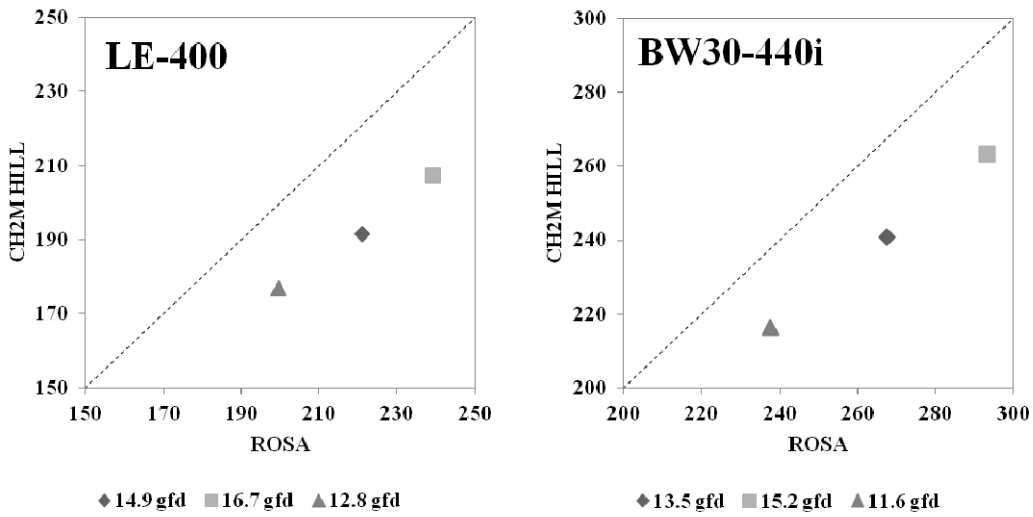


Figure B.2. Bonita DOW Feed Pressure (psi)

B.1.3 Bonita—ToryDS

Table B.3. Bonita Toray Comparison

			Toray			CH2M HILL			%
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Change in Feed Pres.
1	TML20-400	14.9	266.92	23.1	32.93	249.09	17.7	38.9	-7%
2	TML20-400	16.7	290.84	21.0	38.69	273.01	15.9	46.5	-6%
3	TML20-400	12.8	239.37	26.3	26.7	223.79	21.5	30.5	-7%
4	TM720L-430	13.8	218.77	42.9	36.65	209.34	38.5	52.4	-4%
5	TM720L-430	15.6	235.25	38.3	43.38	227.70	35.5	62.3	-3%
6	TM720L-430	11.9	199.49	50.0	29.43	190.63	50.4	40.7	-4%

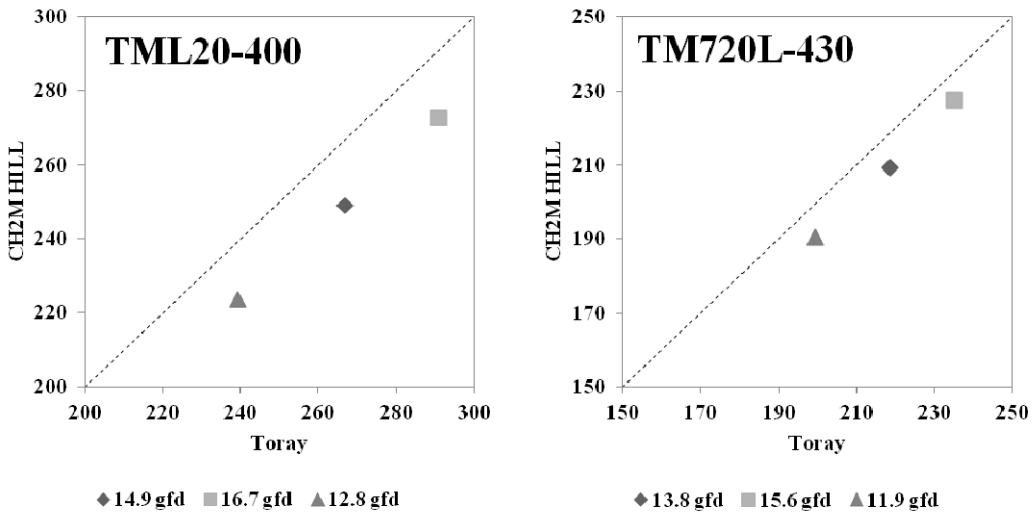


Figure B.3. Bonita Toray Feed Pressure (psi)

B.2 Projection Validation. Kwinana

B.2.1 IMS Design

Table B.4. Kwinana Hydranautics Comparison

			IMS Design			CH2M HILL			%
Case	**Element**	**Flux (gfd)**	**Feed Pressure (psig)**	**Permeate TDS (mg/L)**	**dP (psid)**	**Feed Pressure (psig)**	**Permeate TDS (mg/L)**	**dP (psid)**	**Change in Feed Pres.**
1	SWC4B	7.8	820.7	129.0	15.9	766.8	112.9	12.6	-7%
2	SWC4B	9.0	859.9	110.7	20.3	806.4	97.6	15.7	-6%
3	SWC4B	6.6	787.4	152.7	13.1	729.7	132.3	10.0	-7%
4	SWC6	7.8	730.8	275.2	16.0	657.4	207.8	16.7	-10%
5	SWC6	9.0	748.2	235.4	18.9	680.2	179.7	20.8	-9%
6	SWC6	6.6	716.3	327.0	11.6	Did Not Converge			-

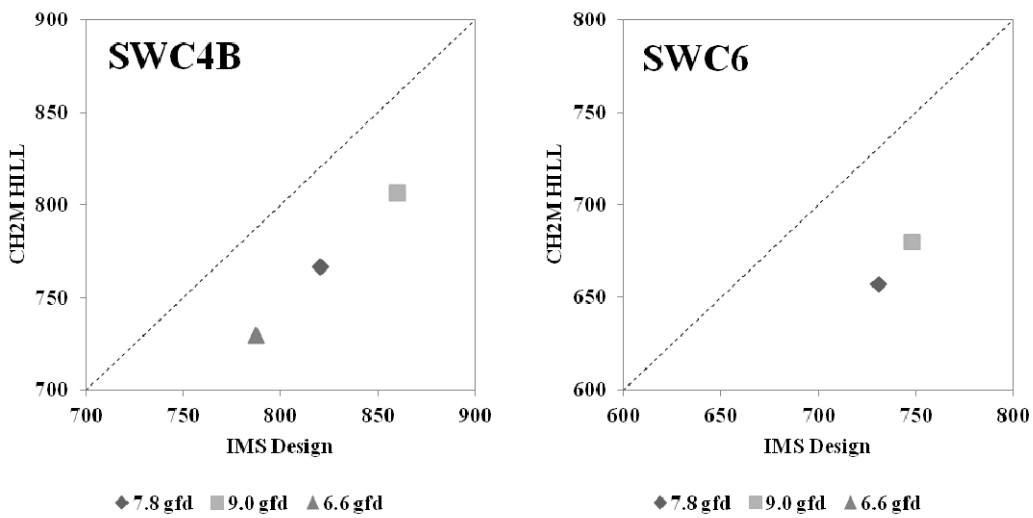


Figure B.4. Kwinana Hydranautics Feed Pressure (psi)

B.2.2 Kwinana—ROSA

Table B.5. Kwinana DOW Comparison

			ROSA			CH2M HILL			% Change in Feed Pres.
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	
1	SW XHR-400i	7.8	833.9	110.8	22.0	788.3	94.9	15.1	-5%
2	SW XHR-400i	9.0	876.2	95.4	26.2	831.3	82.0	18.8	-5%
3	SW XHR-400i	6.6	796.2	129.2	18.4	748.0	111.3	11.9	-6%
4	SW30ULE-440i	7.1	721.1	360.2	19.4	655.4	314.7	15.1	-9%
5	SW30ULE-440i	8.2	740.1	312.0	23.1	678.2	272.3	18.8	-8%
6	SW30ULE-440i	6.0	703.1	421.4	16.4	Did Not Converge			-

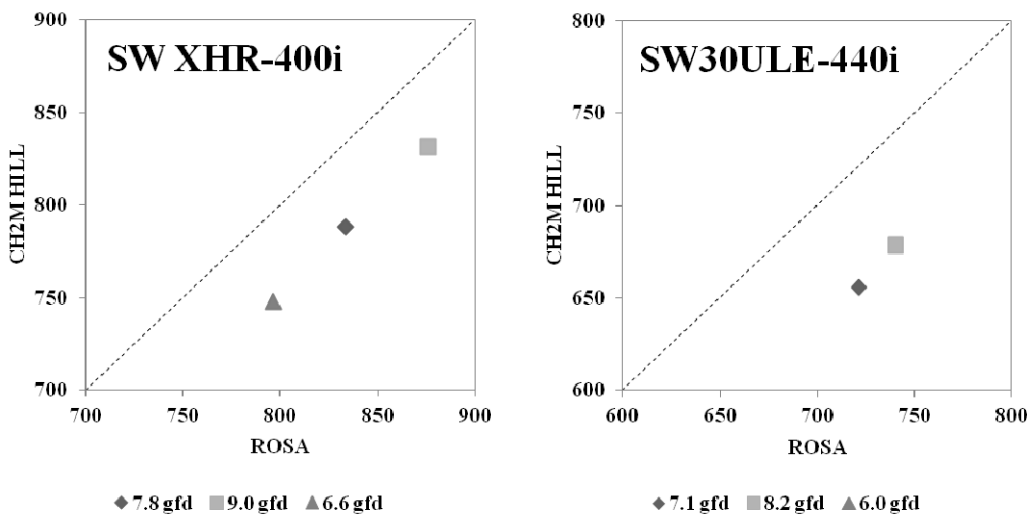


Figure B.5. Kwinana DOW Feed Pressure (psi)

B.2.3 Kwinana—Toray

Table B.6. Kwinana Toray Comparison

			Toray			CH2M HILL			% Change in Feed Pres.
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	
1	TM820-400	7.8	855.7	129.6	11.8	766.5	142.7	12.6	-10%
2	TM820-400	9.0	904.2	114.1	14.3	806.1	123.4	15.7	-11%
3	TM820-400	6.6	813.0	149.8	9.5	729.4	167.2	10.0	-10%
4	TM820F-400	7.8	781.0	214.4	11.5	699.8	236.5	15.1	-10%
5	TM820F-400	9.0	811.6	187.0	14.0	729.3	204.6	18.8	-10%
6	TM820F-400	6.6	753.5	249.6	9.3	672.1	277.1	11.9	-11%

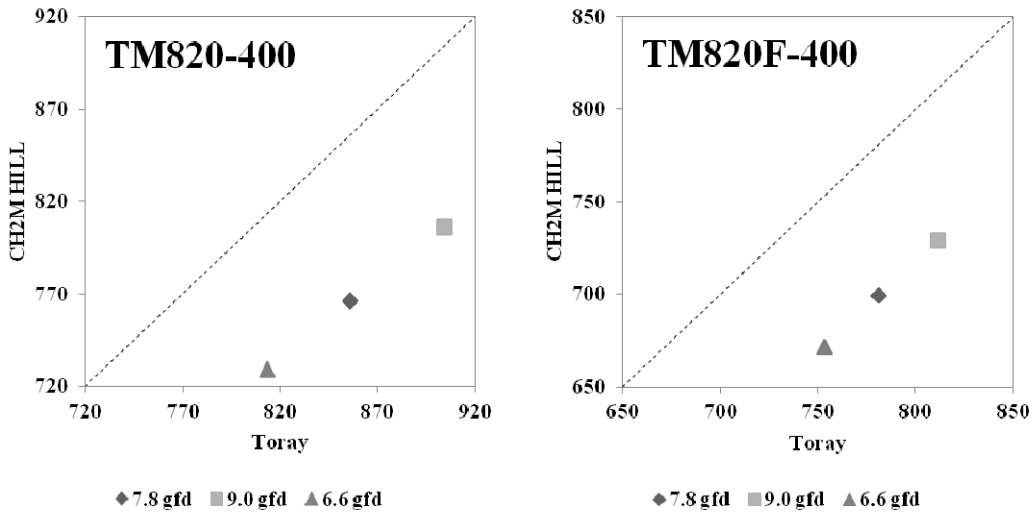


Figure B.6. Kwinana Toray Feed Pressure (psi)

B.3 Capital Cost Validation

Table B.7. Comparison of Tool vs. ADC (MacHarg, 2011)

	ADC	Tool
	(kWh/1000 gal)	
SEC (with ERI PX)	1.59/1.7*	1.65

*1.59 for new membranes, 1.7 with 5 year membrane life

Table B.8. Capital Cost of ERD Equipment/RO Train

	Capital Cost	
ERD Equipment/RO Train	**ADC**	**Tool**
BPX-300 (2)	$64,000	$62,000
Interstage/Boost Pump w/ VFD	$62,500	$66,900
Instrumentation	$15,000	$16,000
Piping and Fittings	$23,500	$14,600
Valving	$15,000	$9,000
Programming	$7,000	
Engineering	$25,000	$38,000
Construction Installation	$60,000	$58,200**
Startup/Commissioning	$3,000	
Contingency	$27,500	$46,200***
TOTAL	$302,500	$311,200

** Tool Installation factor is 35%

***Tool Contingencies include 10%, plus 10% engineering, plus 10% profit, plus 1% electrical, plus 2% mechanical

Appendix C

Visual Basic for Applications Code

The main procedures used to estimate the net driving pressure are shown in the following. The entire Visual Basic code can be viewed in Excel by opening the Visual Basic Editor (Alt+F11 on PCs once Excel is open).

Module 2

```
Sub CalcProjections()
'main routine to estimate required feed pressure
'Get information from tool inputs
Temperature = Worksheets("Water Quality").Range("Temp_C")
FeedpH = Worksheets("Water Quality").Range("pH_input")
RealRecovery = Worksheets("Summary").Range("Recovery")
S1BackPress = 0
S2BackPress = 0
If Worksheets("Summary").OptionButton20 = False Then 'inputs come in as english units
SheetFeedFlow = Range("FeedFlow") 'gpd
SheetPermFlow = Range("PermFlow") 'gpd
BPPress(1) = Range("BP1Press") 'psi
BPPress(2) = Range("BP2Press") 'psi
S1BackPress = Range("PermBackPress") 'psi
S2BackPress = Range("Perm2BackPress") 'psi
Else 'inputs come in as metric units
SheetFeedFlow = Range("FeedFlow") / 0.003785 'm3/d to gpd
SheetPermFlow = Range("PermFlow") / 0.003785 'm3/d to gpd
BPPress(1) = Range("BP1Press") / 6.895 'kPa to psi
BPPress(2) = Range("BP2Press") / 6.895 'kPa to psi
S1BackPress = Range("PermBackPress") / 6.895 'kPa to psi
S2BackPress = Range("Perm2BackPress") / 6.895 'kPa to psi
End If

'Bring in number of vessels for each stage
NumVessels(1) = Range("NVesselsS1")
NumStages = Worksheets("BWRO Flow Balance").Range("NumStages")
If NumStages > 1 Then
NumVessels(2) = Range("NVesselsS2")
Else
NumVessels(2) = 0
End If
If NumStages > 2 Then
NumVessels(3) = Range("NVesselsS3")
Else
NumVessels(3) = 0
End If
```

```
TotVessels = (NumVessels(1) + NumVessels(2) + NumVessels(3))

'Get information for bypass flow and make first guess
DesiredTDS = Worksheets("Water Quality").Range("BypassTDS")
FeedTDS = Worksheets("Water Quality").Range("FeedTDS")
CombinedPermTDS = 100000
If Worksheets("Summary").CheckBox2 = True Then
GuessBypassFlow = SheetPermFlow * (DesiredTDS - FeedTDS * 0.01) / (FeedTDS * 0.99)
If GuessBypassFlow < 0 Then GuessBypassFlow = TotPermFlow * 0.01
Else
GuessBypassFlow = 0
End If
l = 0

'Begin first loop for bypass flows.
'Guess bypass flow required to meet TDS needs based on 99% removal. May not be correct.
'Return to this step until within 10% of required TDS.
Do While Abs(DesiredTDS - CombinedPermTDS) / DesiredTDS > 0.1
l = l + 1
If l = 25 Then 'Only allow 25 iterations to find correct bypass flow.
MsgBox ("Error: Could not find accurate bypass flow.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If

'Redefine main flow streams without bypass flow
TotPermFlow = SheetPermFlow - GuessBypassFlow
TotFeedFlow = TotPermFlow / RealRecovery
TotConcFlow = TotFeedFlow – TotPermFlow

'Assume equal feed flow to each S1 vessel
FeedFlow = TotFeedFlow / NumVessels(1)
If FeedFlow > 115200 Then 'gpd
MsgBox ("Error: Greater than 80 gpm feed flow to a stage 1 vessel. Reconfigure system to
view projections.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If

'First guess at perm flow on a vessel by vessel basis
'Assumes same perm flow for each vessel
PermFlow = TotPermFlow / TotVessels
ConcFlow = FeedFlow - PermFlow
Recovery = PermFlow / FeedFlow

InitializeIons 'Initialize ions procedure: initialize charge, weight, name
OsmoticPressure(1) = OsmoticPressureCalc(FeedIons(), Temperature) 'Calc osmotic
pressure procedure
Istr(1) = IonicStrength(FeedIons()) 'Calc Ionic Strength procedure
```

```
dp(1) = DeltaPressure(FeedFlow, ConcFlow, SpacerThickness(1), NumElements(1))
'procedure to get dp for S1
GetElementData 'procedure to get BetaCoef, AValue, BValue based on selected membrane

'Calculate the total area of all vessels
VesselArea(1) = Area(1) * NumElements(1)
VesselArea(2) = Area(2) * NumElements(2)
VesselArea(3) = Area(3) * NumElements(3)
StageArea(1) = VesselArea(1) * NumVessels(1)
StageArea(2) = VesselArea(2) * NumVessels(2)
StageArea(3) = VesselArea(3) * NumVessels(3)
AreaTot = StageArea(1) + StageArea(2) + StageArea(3)

s = 1 'First stage
'First guess at the feed pressure
FirstPressure = (PermFlow / 24 / 60 / 15850 / (VesselArea(1) / 10.76) / Avalue(1) * 14.7) * (1
- FluxDecline(s)) ^ MembraneAge(s) + dp(s) / 2 + OsmoticPressure(s) * 1.5
'15850 converts from gpm to m3/sec; 14.7 converts from atm to psi
dp(s) = DeltaPressure(FeedFlow, ConcFlow, SpacerThickness(s), NumElements(s))
NewPressure = FirstPressure

'First guess at net driving pressure based on first pressure
PNet = (NewPressure - OsmoticPressure(s) * 1.5 - dp(s) / 2 - S1BackPress) * (1 -
FluxDecline(s)) ^ MembraneAge(s)
FirstSaltPass = Bvalue(s) / (NewPressure / 14.7 * Avalue(s) + Bvalue(s)) 'no units
nIters = 0
CalcTotPermFlow = 0

'Begin loop to estimate the feed pressure. This is the main loop for the program and is based
on code from TFSP.
Do While Abs(TotPermFlow - CalcTotPermFlow) / TotPermFlow > 0.0005 Or nIters < 5
nIters = nIters + 1
If nIters > 150 Then 'Stop the program after 150 attempts to converge
MsgBox ("The program failed to converge. Please verify that all inputs are accurate.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If
s = 1
FeedFlow = TotFeedFlow / NumVessels(1)
For i = 1 To LastIon
ProjFeedIons(i) = FeedIons(i)
If nIters = 1 Then
        'Set a first guess for beta since it cannot be calculated yet and use it to guess
      permeate and concentrate concentrations
Beta = 1.05
PermConc(i, s) = FirstSaltPass * IONS(i).Pass * FeedIons(i) 'Calculate first guess at ions
ConcConc(i, s) = (FeedIons(i) * FeedFlow - PermConc(i, s) * PermFlow) / ConcFlow
End If
TotConcConc(i) = TotFeedFlow * FeedIons(i) / TotConcFlow 'estimation
If NumStages = 1 Then ConcConc(i, s) = TotConcConc(i)
```

```
If ConcConc(i, s) = 0 Then
MembDiffCalc(i) = (ProjFeedIons(i) + ConcConc(i, s)) / 2 - PermConc(i, s)
Else
If ConcConc(i, s) = ProjFeedIons(i) Then
MsgBox ("The program failed to converge. Please verify that all inputs are accurate.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If
MembDiffCalc(i) = Beta * (ProjFeedIons(i) - ConcConc(i, s)) / Log(ProjFeedIons(i) /
ConcConc(i, s)) - PermConc(i, s)
End If
Next i
'Pass through CO2
PermConc(SP_CO2, s) = ProjFeedIons(SP_CO2)
ConcConc(SP_CO2, s) = ProjFeedIons(SP_CO2)

'For future iterations, bring in the pressure from the end of the previous iteration
Pressure(s) = NewPressure
'Use the initial concentrations to guess the osmotic pressure at the membrane
BreakOsPress = OsmoticPressureCalc(MembDiffCalc(), Temperature)

'Recalculate PNet with the updated pressure and osmotic pressure
PNet = (Pressure(s) - BreakOsPress - dp(s) / 2 - S1BackPress) * (1 - FluxDecline(s)) ^
MembraneAge(s)

'CalcPermFlow per vessel
CalcPermFlow(s) = Avalue(s) * VesselArea(s) / 10.76 * PNet / 14.7 * 15850 * 24 * 60 'gpd
CalcPermFlow(2) = 0
CalcPermFlow(3) = 0

    'Now calculate the beta coefficient and use it to recalculate permeate and concentrate
    concentrations
If CalcPermFlow(s) <= 0 Then
CalcPermFlow(s) = 0
CalcRecovery = 0
Beta = 1
Else
CalcRecovery = CalcPermFlow(s) / FeedFlow
Beta = Exp(BetaCoef(s) * CalcRecovery) 'Beta Coefficient
End If
CalcConcFlow(s) = FeedFlow - CalcPermFlow(s)
If CalcConcFlow(s) < 0 Then CalcConcFlow(s) = 0.1 * FeedFlow
dp(s) = DeltaPressure(FeedFlow, CalcConcFlow(s), SpacerThickness(s), NumElements(s))

'Calc salt pass and use it to recalculate concentrations with new PNet
SaltPass = Beta * Bvalue(s) / (PNet / 14.7 * Avalue(s) + Bvalue(s))
For i = 1 To LastIon
PermConc(i, s) = SaltPass * IONS(i).Pass * ProjFeedIons(i)
ConcConc(i, s) = (ProjFeedIons(i) * FeedFlow - PermConc(i, s) * CalcPermFlow(s)) /
CalcConcFlow(s)
```

```
Next i

'send information for next stages
ConcPress(s) = Pressure(s) - dp(s)
Do While s < NumStages ' same routine for 2 and 3 stage systems
s = s + 1
FeedFlow = CalcConcFlow(s - 1) * NumVessels(s - 1) / NumVessels(s)

'Add in boost from interstage ERD or booster pumps
If nIters = 1 Then
TurboBoost = 0
IsoBoost = 0
Else
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
And NumStages > 1 Then
If Worksheets("Summary").OptionButton18 = True And s = 2 Then
TurboBoost = CalcTurboBoost(ConcPress(NumStages), TotConcFlow, FeedFlow *
NumVessels(s), s)
Else
If Worksheets("Summary").OptionButton19 = True And s = 3 Then
TurboBoost = CalcTurboBoost(ConcPress(NumStages), TotConcFlow, FeedFlow *
NumVessels(s), s)
Else
TurboBoost = 0
End If
End If
End If
If Worksheets("Summary").OptionButton13 = True And NumStages > 1 And s = 2 Then
IsoBoost = CalcIsoBoost(ConcPress(NumStages), Pressure(1))
End If
End If
If Worksheets("Summary").OptionButton13 = True And NumStages > 1 And s = 2 Then
BPPress(1) = BPPress(1) + IsoBoost
Pressure(s) = ConcPress(s - 1) + BPPress(s - 1) + TurboBoost

        'Estimate the Salt pass with the new pressure including any boost and then calc ion
        concentrations
FirstSaltPass = Bvalue(s) / (Pressure(s) / 14.7 * Avalue(s) + Bvalue(s)) 'no units
For i = 1 To LastIon
ProjFeedIons(i) = ConcConc(i, s - 1)
PermConc(i, s) = FirstSaltPass * IONS(i).Pass * ProjFeedIons(i) 'Calculate first guess at ions
of next stage
ConcConc(i, s) = (ProjFeedIons(i) * FeedFlow - PermConc(i, s) * PermFlow) / ConcFlow
If ConcConc(i, s) = 0 Then
MembDiffCalc(i) = (ProjFeedIons(i) + ConcConc(i, s)) / 2 - PermConc(i, s)
Else
MembDiffCalc(i) = Beta * (ProjFeedIons(i) - ConcConc(i, s)) / Log(ProjFeedIons(i) /
ConcConc(i, s)) - PermConc(i, s)
End If
Next i
```

```
'Calculate the osmotic pressure at the membrane and use to calc NDP (PNet)
BreakOsPress = OsmoticPressureCalc(MembDiffCalc(), Temperature)
PNet = (Pressure(s) - BreakOsPress - dp(s - 1) / 2) * (1 - FluxDecline(s)) ^ MembraneAge(s)
If s = 2 Then PNet = (Pressure(s) - BreakOsPress - dp(s - 1) / 2 - S2BackPress) * (1 -
FluxDecline(s)) ^ MembraneAge(s)
If PNet < 0 Then PNet = 0
CalcPermFlow(s) = Avalue(s) * VesselArea(s) / 10.76 * PNet / 14.7 * 15850 * 24 * 60 'gpd
CalcConcFlow(s) = FeedFlow - CalcPermFlow(s)
CalcRecovery = CalcPermFlow(s) / FeedFlow

'Now calc beta coefficient and ion concentrations
Beta = Exp(BetaCoef(s) * CalcRecovery)
SaltPass = Beta * Bvalue(s) / (PNet / 14.7 * Avalue(s) + Bvalue(s))
For i = 1 To LastIon
PermConc(i, s) = SaltPass * IONS(i).Pass * ProjFeedIons(i)
ConcConc(i, s) = (ProjFeedIons(i) * FeedFlow - PermConc(i, s) * CalcPermFlow(s)) /
CalcConcFlow(s)
Next i
dp(s) = DeltaPressure(FeedFlow, CalcConcFlow(s), SpacerThickness(s), NumElements(s))
If CalcPermFlow(s) > 0 Then
ConcPress(s) = Pressure(s) - dp(s)
Else
ConcPress(s) = Pressure(s)
End If
OsmoticPressure(s) = OsmoticPressureCalc(ProjFeedIons(), Temperature)
'OP(1)=adjfeed; OP(2)=S2 feed; OP(3)=S3 feed; OP(4)=S3conc
Istr(s) = IonicStrength(ProjFeedIons())
Loop 'loop back for 3 stage system
For i = 1 To LastIon
ProjFeedIons(i) = ConcConc(i, s)
Next i
OsmoticPressure(s + 1) = OsmoticPressureCalc(ProjFeedIons(), Temperature)
Istr(s) = IonicStrength(ProjFeedIons())
CalcTotPermFlow = CalcPermFlow(1) * NumVessels(1) + CalcPermFlow(2) *
NumVessels(2) + CalcPermFlow(3) * NumVessels(3)

'compare CalcPermFlow with TargetPermFlow and iterate Pressure
DeltaFlow = TotPermFlow - CalcTotPermFlow
DeltaPercent = Abs(TotPermFlow - CalcTotPermFlow) / TotPermFlow
'use a brute force convergence
OldPressure = NewPressure
Select Case DeltaFlow
Case Is > 0 ' the pressure needs to go up
If DeltaPercent > 1 Then
NewPressure = OldPressure + OldPressure * DeltaPercent
ElseIf DeltaPercent > 0.01 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 5
ElseIf DeltaPercent > 0.001 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 8
ElseIf DeltaPercent > 0.0008 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 10
```

```
ElseIf DeltaPercent > 0.0005 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 20
Else
NewPressure = OldPressure
End If
Case Is < 0 ' the pressure needs to go down
If DeltaPercent > 1 Then
NewPressure = OldPressure - OldPressure * DeltaPercent
ElseIf DeltaPercent > 0.01 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 5
ElseIf DeltaPercent > 0.001 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 8
ElseIf DeltaPercent > 0.0008 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 10
ElseIf DeltaPercent > 0.0005 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 20
Else
NewPressure = OldPressure
End If
End Select
Loop ‘loop back to amin projections routine

S1PermFlow = CalcPermFlow(1) * NumVessels(1)
S1ConcFlow = TotFeedFlow - S1PermFlow
S2PermFlow = CalcPermFlow(2) * NumVessels(2)
S2ConcFlow = S1ConcFlow - S2PermFlow
S3PermFlow = CalcPermFlow(3) * NumVessels(3)
S3ConcFlow = S2ConcFlow - S3PermFlow
PermTDS = 0
For i = 1 To LastIon
TotPermConc(i) = (PermConc(i, 1) * S1PermFlow + PermConc(i, 2) * S2PermFlow +
PermConc(i, 3) * S3PermFlow) / CalcTotPermFlow
Perm1Conc(i) = PermConc(i, 1)
Perm2Conc(i) = PermConc(i, 2)
Perm3Conc(i) = PermConc(i, 3)
BlendedPermConc(i) = (FeedIons(i) * GuessBypassFlow + TotPermConc(i) * TotPermFlow)
/ (TotPermFlow + GuessBypassFlow)
PermTDS = PermTDS + TotPermConc(i)
Next i

If Worksheets("Summary").CheckBox2 = True Then
CombinedPermTDS = (FeedTDS * GuessBypassFlow + PermTDS * TotPermFlow) /
(TotPermFlow + GuessBypassFlow)
If (DesiredTDS - CombinedPermTDS) / DesiredTDS > 0.1 Then
GuessBypassFlow = GuessBypassFlow * 1.1
End If
If (DesiredTDS - CombinedPermTDS) / DesiredTDS < -0.1 Then
GuessBypassFlow = GuessBypassFlow * 0.9
End If
Else
CombinedPermTDS = DesiredTDS
```

```
End If
Loop ‘loop back to bypass flow calc

‘check to make sure no rules of thumb are broken
If Pressure(1) > 1200 Then
MsgBox ("Error: Feed pressure is greater than 1200 psi. Please revise system design.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
If Worksheets("Membrane Database").Range("S1Application") = "BWRO" Then
If Pressure(1) > 600 Then
MsgBox ("Error: Feed pressure is greater than 600 psi. Please select a SWRO membrane.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
End If
If NumStages > 1 Then
If CalcConcFlow(1) * NumVessels(1) / NumVessels(2) > 115200 Then 'gpd
MsgBox ("Error: Greater than 80 gpm feed flow to a stage 2 vessel. Reconfigure system to
view projections.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
End If
If NumStages > 2 Then
If CalcConcFlow(2) * NumVessels(2) / NumVessels(3) > 115200 Then 'gpd
MsgBox ("Error: Greater than 80 gpm feed flow to a stage 3 vessel. Reconfigure system to
view projections.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
End If

‘prepare information to be written out to tool
OsmoticPressure(5) = OsmoticPressureCalc(Perm1Conc(), Temperature)
OsmoticPressure(6) = OsmoticPressureCalc(Perm2Conc(), Temperature)
OsmoticPressure(7) = OsmoticPressureCalc(Perm3Conc(), Temperature)
OsmoticPressure(8) = OsmoticPressureCalc(TotPermConc(), Temperature)
OsmoticPressure(9) = OsmoticPressureCalc(BlendedPermConc(), Temperature)
'OP(5)=S1 perm; OP(6)=S2 perm; OP(7)=S3 perm; OP(8)=tot perm; OP(9)=blended perm
Istr(5) = IonicStrength(Perm1Conc())
Istr(6) = IonicStrength(Perm2Conc())
Istr(7) = IonicStrength(Perm3Conc())
Istr(8) = IonicStrength(TotPermConc())
Istr(9) = IonicStrength(BlendedPermConc())
Worksheets("Cost Summary").Range("NoERDkW") = "N/A"
Worksheets("Cost Summary").Range("NoERDCost") = "N/A"
PutDataOnSheets ‘procedure that writes out to the tool
End Sub

Public Sub InitializeIons()
```

```
'Store ion information

'Charge
IONS(SP_Ca).Charge = 2
IONS(SP_Mg).Charge = 2
IONS(SP_Na).Charge = 1
IONS(SP_K).Charge = 1
IONS(SP_NH4).Charge = 1
IONS(SP_Sr).Charge = 2
IONS(SP_Ba).Charge = 2
IONS(SP_Fe3).Charge = 3
IONS(SP_Al).Charge = 3
IONS(SP_B).Charge = 3
IONS(SP_CO3).Charge = -2
IONS(SP_HCO3).Charge = -1
IONS(SP_CO2).Charge = -2
IONS(SP_SO4).Charge = -2
IONS(SP_Cl).Charge = -1
IONS(SP_Br).Charge = -1
IONS(SP_NO3).Charge = -1
IONS(SP_F).Charge = -1
IONS(SP_PO4).Charge = -3
IONS(SP_SiO2).Charge = 2

'Molecular Weight
IONS(SP_Ca).MolWt = 40.08
IONS(SP_Mg).MolWt = 24.305
IONS(SP_Na).MolWt = 22.99
IONS(SP_K).MolWt = 39.098
IONS(SP_NH4).MolWt = 18.04
IONS(SP_Sr).MolWt = 87.62
IONS(SP_Ba).MolWt = 137.34
IONS(SP_Fe3).MolWt = 55.847
IONS(SP_Al).MolWt = 26.98154
IONS(SP_B).MolWt = 10.811
IONS(SP_CO3).MolWt = 60.01
IONS(SP_HCO3).MolWt = 61.01
IONS(SP_CO2).MolWt = 44.04
IONS(SP_SO4).MolWt = 96.06
IONS(SP_Br).MolWt = 79.904
IONS(SP_Cl).MolWt = 35.45
IONS(SP_NO3).MolWt = 62.005
IONS(SP_F).MolWt = 19
IONS(SP_PO4).MolWt = 94.9738
IONS(SP_SiO2).MolWt = 60.08

'Name
IONS(SP_Na).Name = "Na = 1"
IONS(SP_K).Name = "K = 2"
IONS(SP_Ca).Name = "Ca = 3"
IONS(SP_Mg).Name = "Mg = 4"
```

```
IONS(SP_Sr).Name = "Sr = 5"
IONS(SP_Ba).Name = "Ba = 6"
IONS(SP_Al).Name = "Al = 7"
IONS(SP_Fe3).Name = "Fe3 = 8"
IONS(SP_NH4).Name = "NH4 = 9"
IONS(SP_HCO3).Name = "HCO3 = 10"
IONS(SP_CO2).Name = "CO2 = 11"
IONS(SP_CO3).Name = "CO3 = 12"
IONS(SP_Br).Name = "Br = 13"
IONS(SP_Cl).Name = "Cl = 14"
IONS(SP_F).Name = "F = 15"
IONS(SP_SO4).Name = "SO4 = 16"
IONS(SP_NO3).Name = "NO3 = 17"
IONS(SP_PO4).Name = "PO4 = 18"
IONS(SP_SiO2).Name = "SiO2 = 19"

'Input values
FeedIons(SP_Na) = Range("User_Na").Value
FeedIons(SP_K) = Range("User_K").Value
FeedIons(SP_Ca) = Range("User_CA").Value
FeedIons(SP_Mg) = Range("User_MG").Value
FeedIons(SP_Sr) = Range("User_SR").Value
FeedIons(SP_Ba) = Range("User_BA").Value
FeedIons(SP_Al) = Range("User_AL").Value
FeedIons(SP_Fe3) = Range("User_FE3").Value
FeedIons(SP_B) = Range("User_B").Value
FeedIons(SP_NH4) = Range("User_NH4").Value
FeedIons(SP_HCO3) = Range("User_HCO3").Value
FeedIons(SP_CO2) = Range("User_CO2").Value
FeedIons(SP_CO3) = Range("User_CO3").Value
FeedIons(SP_Br) = Range("User_BR").Value
FeedIons(SP_Cl) = Range("User_CL").Value
FeedIons(SP_F) = Range("User_F").Value
FeedIons(SP_SO4) = Range("User_SO4").Value
FeedIons(SP_NO3) = Range("User_NO3").Value
FeedIons(SP_PO4) = Range("User_PO4").Value
FeedIons(SP_SiO2) = Range("User_SIO2").Value

'Account for leakage flow across Isobaric ERD
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Isobaric" Then
For i = 1 To LastIon
Leakage = Range("IsoLeak")
FeedIons(i) = FeedIons(i) + Leakage * FeedIons(i) / (1 - Recovery)
Next i
End If

'passage coefficients - all relative to Na and Cl
IONS(SP_Ca).Pass = 0.25
IONS(SP_Mg).Pass = 0.25
IONS(SP_Na).Pass = 1
IONS(SP_K).Pass = 1.3
```

```
IONS(SP_NH4).Pass = 2
IONS(SP_Sr).Pass = 0.25
IONS(SP_Ba).Pass = 0.25
IONS(SP_Fe3).Pass = 0.25
IONS(SP_Al).Pass = 0.25
IONS(SP_B).Pass = 40
IONS(SP_CO3).Pass = 0.25
IONS(SP_HCO3).Pass = 1
IONS(SP_CO2).Pass = 0.25
IONS(SP_SO4).Pass = 0.25
IONS(SP_Cl).Pass = 1
IONS(SP_Br).Pass = 1.3
IONS(SP_NO3).Pass = 1.5
IONS(SP_F).Pass = 0.7
IONS(SP_PO4).Pass = 0.2
IONS(SP_SiO2).Pass = 0.75
End Sub

Sub GetElementData()
'Read information from Membrane selection worksheet and calculate beta coefficient and membrane specific passage coefficients

S1ElemFlow = Range("S1ElemFlow") 'gpd
S1ElemPress = Range("S1ElemPress") 'psi
S1ElemTDS = Range("S1ElemTDS") 'mg/L
S1ElemRej = Range("S1ElemRej") / 100 '%
Area(1) = Range("S1Area") 'sf
S1ElemLength = Range("S1ElemLength") 'in
S1ElemRecovery = Range("S1ElemRec") / 100 'in
SpacerThickness(1) = Range("S1SpaceThick")
NumElements(1) = Range("NumS1Elements")
S1AdjustedLength = S1ElemLength * NumElements(1)
MembraneAge(1) = Range("S1MemAge")
FluxDecline(1) = Range("S1FluxDec")

ATempCorr = Exp((1 / (273 + Temperature) - 1 / 298) * 3020)
S1CalcConcentration = ((S1ElemFlow / S1ElemRecovery) * S1ElemTDS - S1ElemFlow *
S1ElemTDS * (1 - S1ElemRej)) / (S1ElemFlow / S1ElemRecovery * (1 - S1ElemRecovery))
'mg/L
S1ConcentrationDiff = (S1ElemTDS + S1CalcConcentration) / 2 - S1ElemTDS * (1 -
S1ElemRej) 'mg/L
Bvalue(1) = S1ElemFlow * S1ElemTDS * (1 - S1ElemRej) / (Area(1) *
S1ConcentrationDiff) / 2120315 / ATempCorr
"(mg/L)*(gal/day)*(1 day/86400 s)*(1ft3/7.48 gal)*(0.3048m/ft)/(ft2*mg/L)=m/s
Avalue(1) = S1ElemFlow / (Area(1) * (S1ElemPress - OsmoticPressure(1))) / 144239 /
ATempCorr
'(gal/day)*(1day/86400s)*(1ft3/7.48gal)*(.3048m/ft)*(14.7psi/atm)/(ft2*psi) - convert to
m/s/atm
BetaCoef(1) = -0.3492 * Log(S1AdjustedLength) + 2.0152

S2ElemFlow = Range("S2ElemFlow") 'gpd
```

```
S2ElemPress = Range("S2ElemPress") 'psi
S2ElemTDS = Range("S2ElemTDS") 'mg/L
S2ElemRej = Range("S2ElemRej") / 100 '%
Area(2) = Range("S2Area") 'sf
S2ElemLength = Range("S2ElemLength") 'in
S2ElemRecovery = Range("S2ElemRec") / 100 'in
SpacerThickness(2) = Range("S2SpaceThick")
NumElements(2) = Range("NumS2Elements")
S2AdjustedLength = S2ElemLength * NumElements(2)
MembraneAge(2) = Range("S2MemAge")
FluxDecline(2) = Range("S2FluxDec")

S2CalcConcentration = ((S2ElemFlow / S2ElemRecovery) * S2ElemTDS - S2ElemFlow *
S2ElemTDS * (1 - S2ElemRej)) / (S2ElemFlow / S2ElemRecovery * (1 - S2ElemRecovery))
'mg/L
S2ConcentrationDiff = (S2ElemTDS + S2CalcConcentration) / 2 - S2ElemTDS * (1 -
S2ElemRej) 'mg/L
Bvalue(2) = S2ElemFlow * S2ElemTDS * (1 - S2ElemRej) / (Area(2) *
S2ConcentrationDiff) / 2120315 / ATempCorr
"(mg/L)*(gal/day)*(1 day/86400 s)*(1ft3/7.48 gal)*(0.3048m/ft)/(ft2*mg/L)=m/s
Avalue(2) = S2ElemFlow / (Area(2) * (S2ElemPress - OsmoticPressure(1))) / 144239 /
ATempCorr
'(gal/day)*(1day/86400s)*(1ft3/7.48gal)*(.3048m/ft)*(14.7psi/atm)/(ft2*psi) - convert to
m/s/atm
BetaCoef(2) = 0
If NumStages > 1 Then
BetaCoef(2) = -0.3492 * Log(S2AdjustedLength) + 2.0152
End If

S3ElemFlow = Range("S3ElemFlow") 'gpd
S3ElemPress = Range("S3ElemPress") 'psi
S3ElemTDS = Range("S3ElemTDS") 'mg/L
S3ElemRej = Range("S3ElemRej") / 100 '%
Area(3) = Range("S3Area") 'sf
S3ElemLength = Range("S3ElemLength") 'in
S3ElemRecovery = Range("S3ElemRec") / 100 'in
SpacerThickness(3) = Range("S3SpaceThick")
NumElements(3) = Range("NumS3Elements")
S3AdjustedLength = S3ElemLength * NumElements(3)
MembraneAge(3) = Range("S3MemAge")
FluxDecline(3) = Range("S3FluxDec")

S3CalcConcentration = ((S3ElemFlow / S3ElemRecovery) * S3ElemTDS - S3ElemFlow *
S3ElemTDS * (1 - S3ElemRej)) / (S3ElemFlow / S3ElemRecovery * (1 - S3ElemRecovery))
'mg/L
S3ConcentrationDiff = (S3ElemTDS + S3CalcConcentration) / 2 - S3ElemTDS * (1 -
S3ElemRej) 'mg/L
Bvalue(3) = S3ElemFlow * S3ElemTDS * (1 - S3ElemRej) / (Area(3) *
S3ConcentrationDiff) / 2120315 / ATempCorr
"(mg/L)*(gal/day)*(1 day/86400 s)*(1ft3/7.48 gal)*(0.3048m/ft)/(ft2*mg/L)=m/s
```

```
Avalue(3) = S3ElemFlow / (Area(3) * (S3ElemPress - OsmoticPressure(1))) / 144239 /
ATempCorr
'(gal/day)*(1day/86400s)*(1ft3/7.48gal)*(.3048m/ft)*(14.7psi/atm)/(ft2*psi) - convert to
m/s/atm
BetaCoef(3) = 0
If NumStages > 2 Then
BetaCoef(3) = -0.3492 * Log(S3AdjustedLength) + 2.0152
End If
End Sub

Public Function CalcTurboBoost(TConcPress As Double, TConcFlow As Double,
'Calculate the interstage turbo boost

If Worksheets("Summary").OptionButton20 = False Then
TPermPress = Worksheets("Summary").Range("PermPress")
Else
TPermPress = Worksheets("Summary").Range("PermPress") / 6.895 'kPa to psi
End If
RowStart = Worksheets("Turbocharger ERD Selection").Range("TurboTableStart").row
ColumnStart = Worksheets("Turbocharger ERD
Selection").Range("TurboTableStart").Column
TurboModelStart = Worksheets("Turbocharger ERD
Selection").Range("TurboModelStart").Column
If Worksheets("Turbocharger ERD Selection").OptionButton1 = True Then
i = 1 'ERI
If Worksheets("Membrane Database").Range("S1Application") = "SWRO" Then i = 9
Else
i = 25 'Fedco
End If
TableFlow = 0
Do While TFeedFlow / 1440 > TableFlow
TableFlow = Worksheets("Turbocharger ERD Selection").Cells(RowStart + i,
ColumnStart).Value
i = i + 1
Loop
If i = 1 Then i = 2
Worksheets("Turbocharger ERD Selection").Range("TurboModel") =
Worksheets("Turbocharger ERD Selection").Cells(RowStart + i - 1, TurboModelStart)
SystemConcPress = Worksheets("Turbocharger ERD Selection").Cells(RowStart + i - 1,
TurboModelStart + 8)
'Find the smallest model that will work for the system and calc efficiency based on
manufacturer's equations
ModelNum = Worksheets("Turbocharger ERD Selection").Cells(RowStart + i - 1,
TurboModelStart - 1)
If ModelNum < 9 Then
TurboEff = (2.27331E-11 * (TFeedFlow / 1440) ^ 3) - (0.000000157469 * (TFeedFlow /
1440) ^ 2) + (0.000357 * (TFeedFlow / 1440)) + 0.479619722
ElseIf ModelNum < 19 Then
TurboEff = (0.000000000064769 * (TFeedFlow / 1440) ^ 3) - (0.000000235344 *
(TFeedFlow / 1440) ^ 2) + (0.000307834 * (TFeedFlow / 1440)) + 0.553423744
ElseIf ModelNum < 25 Then
```

```
TurboEff = (-3.098E-14 * (TFeedFlow / 1440) ^ 3) - (1.88805E-12 * (TFeedFlow / 1440) ^
2) + (0.0000133228 * (TFeedFlow / 1440)) + 0.70108
Else
TurboEff = 0.038728 * WorksheetFunction.Ln(TFeedFlow / 1440) + 0.471545
End If
If TFeedFlow = 0 Then
Boost = 0
Else
RejectRatio = TConcFlow / TFeedFlow
If Worksheets("Turbocharger ERD Selection").OptionButton1 = True Then
If RejectRatio < 0.6 Then
TurboEff = TurboEff - (Abs(RejectRatio - 0.6)) ^ 1.55
Else
If RejectRatio > 0.7 Then
TurboEff = TurboEff - (Abs(RejectRatio - 0.7)) ^ 2
End If
End If
End If
Worksheets("Turbocharger ERD Selection").Range("TurboEff") = TurboEff
Boost = (TConcPress + TPermPress - SystemConcPress) * TConcFlow / TFeedFlow *
TurboEff
End If
CalcTurboBoost = 0
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
Then
If Worksheets("Summary").OptionButton20 = False Then
Worksheets("Turbocharger ERD Selection").Range("TurboBoost") = Boost
Worksheets("Turbocharger ERD Selection").Range("TurboFeedFlow") = TFeedFlow / 1440
Worksheets("Turbocharger ERD Selection").Range("TurboMinConcPress") =
SystemConcPress 'psi
Worksheets("Summary").InputConcPress = SystemConcPress 'psi
Else
Worksheets("Turbocharger ERD Selection").Range("TurboBoost") = Boost * 6.895 'psi to
kPa
Worksheets("Turbocharger ERD Selection").Range("TurboFeedFlow") = TFeedFlow / 1440 /
(3.785 / 60) 'gpm to L/s
Worksheets("Turbocharger ERD Selection").Range("TurboMinConcPress") =
SystemConcPress * 6.895 'psi to kPa
Worksheets("Summary").InputConcPress = SystemConcPress * 6.895 'psi to kPa
End If
If Worksheets("Summary").OptionButton18 = True Then
If Stage = 2 Then CalcTurboBoost = Boost
End If
If Worksheets("Summary").OptionButton19 = True Then
If Stage = 3 Then CalcTurboBoost = Boost
End If
End If
End Function

Public Function CalcIsoBoost(IConcPress As Double, S1FPress As Double) As Double
'Calc the boost provided by the isobaric device
```

```
If Worksheets("Summary").OptionButton20 = False Then
IPermPress = Worksheets("Summary").Range("PermPress")
Else
IPermPress = Worksheets("Summary").Range("PermPress") / 6.895 'kPa to psi
End If

IBoost = (IConcPress + IPermPress) * Worksheets("Isobaric ERD
Selection").Range("IsoEff")
CalcIsoBoost = S1FPress + IPermPress - IBoost
End Function

Public Function DeltaPressure(InfluentFlow As Double, ConcentrateFlow As Double,
'Calculate the loss in pressure between the feed and concentrate streams. Called often
throughout the CalcProjections procedure.

ConcentrateFlow = WorksheetFunction.Max(0, ConcentrateFlow)
FlowAve = (InfluentFlow + ConcentrateFlow) / 2 / 24 / 60 'from gpd to gpm
dpCoef = SpacerThick * -0.000875 + 0.04075
'dp calculated by using the membrane spacer thickness and then validated to hydranautics
membranes
DeltaPressure = NElem * dpCoef * FlowAve ^ 1.5 'sends in psi
End Function

Public Function IonicStrength(IonConcentrations() As Double) As Double
'Calculate the Ionic Strength of a flow stream based on the ion concentrations

floatIonStr = 0
For i = 1 To LastIon
If i <> SP_CO2 Then
' ignores CO2 and organics
If i <> SP_Organic Then
floatIonStr = floatIonStr + IonConcentrations(i) * IONS(i).Charge * IONS(i).Charge /
IONS(i).MolWt
End If
End If
Next i
' Set some nonzero value just in case to avoid division by zero somewhere.
If floatIonStr < 0.0000001 Then floatIonStr = 0.0000001
IonicStrength = floatIonStr / (2 * 1000)
End Function

Public Function OsmoticPressureCalc(OsConcentrations() As Double, ByVal
Temperature As Double) As Double
'Calculate the Osmotic Pressure of a flow stream based on the ion concentrations

PITemp = 0
RT = 0.082054 * (Temperature + 273) ' 14.69 converts answer to psi
RT = RT / 1000 ' convert to moles/l from mm/l
floatDummy = Sqr(IonicStrength(OsConcentrations()))
```

```
For i = 1 To LastIon
' skip CO2
If i <> SP_CO2 Then
' note when Z=0, ActCoef = 1.0 (for SiO2)
z = IONS(i).Charge
If z = 0 Then z = 1
ActCoef = (10 ^ (-0.5 * z * z * floatDummy / (1 + floatDummy))) ^ 0.14
PITemp = PITemp + ActCoef * RT * OsConcentrations(i) / IONS(i).MolWt
End If
Next i
OsmoticPressureCalc = 14.7 * PITemp 'send in psi
End Function
```

Sub PutDataOnSheets()

'After the CalcProjections procedure has finished, print the outputs back to the summary and water quality pages

```
If Worksheets("Summary").OptionButton20 = False Then
Range("ByFlow") = GuessBypassFlow 'gpd
Worksheets("Summary").InputBP1Press = Round(BPPress(1), 1)
Range("S1FeedFlow") = TotFeedFlow / 24 / 60
Range("S1FeedPress") = Pressure(1) + Range("PermPress")
Range("S1PermFlow") = S1PermFlow / 24 / 60
Range("S1PermPress") = Range("PermPress") + S1BackPress
Range("S1ConcFlow") = S1ConcFlow / 24 / 60
Range("S1ConcPress") = ConcPress(1) + Range("PermPress")
Range("S1Recovery") = S1PermFlow / TotFeedFlow
Range("S1Flux") = S1PermFlow / StageArea(1)
If NumStages > 1 Then
Range("S2FeedFlow") = Range("S1ConcFlow")
Range("S2FeedPress") = Pressure(2) + Range("PermPress")
Range("S2PermFlow") = S2PermFlow / 24 / 60
Range("S2PermPress") = Range("PermPress") + S2BackPress
Range("S2ConcFlow") = S2ConcFlow / 24 / 60
Range("S2ConcPress") = ConcPress(2) + Range("PermPress")
Range("S2Recovery") = S2PermFlow / 24 / 60 / Range("S1ConcFlow")
Range("S2Flux") = S2PermFlow / StageArea(2)
Else
Range("S2FeedFlow") = 0
Range("S2FeedPress") = 0
Range("S2PermFlow") = 0
Range("S2PermPress") = 0
Range("S2ConcFlow") = 0
Range("S2ConcPress") = 0
Range("S2Recovery") = 0
Range("S2Flux") = 0
End If
If NumStages > 2 Then
Range("S3FeedFlow") = Range("S2ConcFlow")
Range("S3FeedPress") = Pressure(3) + Range("PermPress")
Range("S3PermFlow") = S3PermFlow / 24 / 60
```

```
Range("S3PermPress") = Range("PermPress")
Range("S3ConcFlow") = S3ConcFlow / 24 / 60
Range("S3ConcPress") = ConcPress(3) + Range("PermPress")
Range("S3Recovery") = S3PermFlow / 24 / 60 / Range("S2ConcFlow")
Range("S3Flux") = S3PermFlow / StageArea(3)
Else
Range("S3FeedFlow") = 0
Range("S3FeedPress") = 0
Range("S3PermFlow") = 0
Range("S3PermPress") = 0
Range("S3ConcFlow") = 0
Range("S3ConcPress") = 0
Range("S3Recovery") = 0
Range("S3Flux") = 0
End If
Else
Range("ByFlow") = GuessBypassFlow / 7.48 'gpd to m3/d
Worksheets("Summary").InputBP1Press = Round(BPPress(1) * 6.895, 1) 'psi to kPa
Range("S1FeedFlow") = TotFeedFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S1FeedPress") = Range("PermPress") + Pressure(1) * 6.895 'psi to kPa
Range("S1PermFlow") = S1PermFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S1PermPress") = (Range("PermPress") + S1BackPress) * 6.895 'psi to kPa
Range("S1ConcFlow") = S1ConcFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S1ConcPress") = Range("PermPress") + ConcPress(1) * 6.895 'psi to kPa
Range("S1Recovery") = S1PermFlow / TotFeedFlow
Range("S1Flux") = S1PermFlow / StageArea(1) * 1.697573 'gpf to lmh
If NumStages > 1 Then
Range("S2FeedFlow") = Range("S1ConcFlow")
Range("S2FeedPress") = Pressure(2) * 6.895 + Range("PermPress") 'psi to kPa
Range("S2PermFlow") = S2PermFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S2PermPress") = (Range("PermPress") + S2BackPress) * 6.895 'psi to kPa
Range("S2ConcFlow") = S2ConcFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S2ConcPress") = ConcPress(2) * 6.895 + Range("PermPress") 'psi to kPa
Range("S2Recovery") = S2PermFlow / 24 / 60 / Range("S1ConcFlow") * (3.785 / 60) 'gpm
to L/s
Range("S2Flux") = S2PermFlow / StageArea(2) * 1.697573 'gpf to lmh
Else
Range("S2FeedFlow") = 0
Range("S2FeedPress") = 0
Range("S2PermFlow") = 0
Range("S2PermPress") = 0
Range("S2ConcFlow") = 0
Range("S2ConcPress") = 0
Range("S2Recovery") = 0
Range("S2Flux") = 0
End If

If NumStages > 2 Then
Range("S3FeedFlow") = Range("S2ConcFlow")
Range("S3FeedPress") = Pressure(3) * 6.895 + Range("PermPress") 'psi to kPa
Range("S3PermFlow") = S3PermFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
```

```
Range("S3PermPress") = Range("PermPress")
Range("S3ConcFlow") = S3ConcFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S3ConcPress") = ConcPress(3) * 6.895 + Range("PermPress") 'psi to kPa
Range("S3Recovery") = S3PermFlow / 24 / 60 / Range("S2ConcFlow") * (3.785 / 60) 'gpm
to L/s
Range("S3Flux") = S3PermFlow / StageArea(3) * 1.697573 'gpf to lmh
Else
Range("S3FeedFlow") = 0
Range("S3FeedPress") = 0
Range("S3PermFlow") = 0
Range("S3PermPress") = 0
Range("S3ConcFlow") = 0
Range("S3ConcPress") = 0
Range("S3Recovery") = 0
Range("S3Flux") = 0
End If
End If

Set s = Worksheets("Water Quality")

nCol = Range("AdjFeed").Column
Pcol = Range("ROPermeate").Column
Bcol = Range("BlendedROPermeate").Column
Ccol = Range("ROConcentrate").Column
Pcol1 = Range("S1Permeate").Column
Ccol1 = Range("S1Concentrate").Column
Pcol2 = Range("S2Permeate").Column
Ccol2 = Range("S2Concentrate").Column
Pcol3 = Range("S3Permeate").Column
Ccol3 = Range("S3Concentrate").Column
CRow = Range("ROFeed").row

' Sodium -Na
CRow = CRow + 1
i = SP_Na
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Potassium -k
CRow = CRow + 1
i = SP_K
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
```

```
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Calcium -Ca
CRow = CRow + 1
i = SP_Ca
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Magnesium -Mg
CRow = CRow + 1
i = SP_Mg
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Strontium -Sr
CRow = CRow + 1
i = SP_Sr
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)
```

```
' Barium -Ba
CRow = CRow + 1
i = SP_Ba
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Aluminum - Al+++
CRow = CRow + 1
i = SP_Al
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Ferric Iron - Fe+++ (as Fe)
CRow = CRow + 1
i = SP_Fe3
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Boron - B+++
CRow = CRow + 1
i = SP_B
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
If BlendedPermConc(i) < s.Range("B2Pass") Then
s.Range("B2PPower") = 0
```

```
s.Range("B2PPowerMax") = 0
End If
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Ammonia - NH4 (as NH4)
CRow = CRow + 1
i = SP_NH4
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Hydrogen Ion - H
'run the CO2toPH procedure to calculate the pH of each stream based on the CO2 and total
carbon. This assumes CO2 concentration is the same for all flow streams.
PermConc(SP_CO2, 1) = FeedIons(SP_CO2)
ConcConc(SP_CO2, 1) = FeedIons(SP_CO2)

CRow = CRow + 1
CO2toPH Istr(1), Temperature, FeedIons(SP_HCO3), FeedIons(SP_CO2),
FeedIons(SP_CO3)
HPlus(1) = HPlusCalc
HCO3(1) = HCO3Calc
CO3(1) = CO3Calc
CO2(1) = CO2Calc
CO2toPH Istr(2), Temperature, ConcConc(SP_HCO3, 1), ConcConc(SP_CO2, 1),
ConcConc(SP_CO3, 1)
HPlus(4) = HPlusCalc
HCO3(4) = HCO3Calc
CO3(4) = CO3Calc
CO2(4) = CO2Calc
CO2toPH Istr(5), Temperature, PermConc(SP_HCO3, 1), PermConc(SP_CO2, 1),
PermConc(SP_CO3, 1)
HPlus(5) = HPlusCalc
HCO3(5) = HCO3Calc
CO3(5) = CO3Calc
CO2(5) = CO2Calc
CO2toPH Istr(3), Temperature, ConcConc(SP_HCO3, 2), CO2(4), ConcConc(SP_CO3, 2)
'Send 1st stage concentrate data to 2nd stage perm, concentrate
HPlus(6) = HPlusCalc
```

```
HCO3(6) = HCO3Calc
CO3(6) = CO3Calc
CO2(6) = CO2Calc
CO2toPH Istr(6), Temperature, PermConc(SP_HCO3, 2), CO2(4), PermConc(SP_CO3, 2)
HPlus(7) = HPlusCalc
HCO3(7) = HCO3Calc
CO3(7) = CO3Calc
CO2(7) = CO2Calc
CO2toPH Istr(4), Temperature, ConcConc(SP_HCO3, 3), CO2(6), ConcConc(SP_CO3, 3)
'Send 2nd stage concentrate data to 3rd stage perm, concentrate
HPlus(8) = HPlusCalc
HCO3(8) = HCO3Calc
CO3(8) = CO3Calc
CO2(8) = CO2Calc
CO2toPH Istr(7), Temperature, PermConc(SP_HCO3, 3), CO2(6), PermConc(SP_CO3, 3)
HPlus(9) = HPlusCalc
HCO3(9) = HCO3Calc
CO3(9) = CO3Calc
CO2(9) = CO2Calc
If NumStages = 1 Then ConcConc(SP_CO2, NumStages) = CO2(4)
If NumStages = 2 Then ConcConc(SP_CO2, NumStages) = CO2(6)
If NumStages = 3 Then ConcConc(SP_CO2, NumStages) = CO2(8)
CO2toPH Istr(1 + NumStages), Temperature, ConcConc(SP_HCO3, NumStages),
ConcConc(SP_CO2, NumStages), ConcConc(SP_CO3, NumStages)
HPlus(2) = HPlusCalc
HCO3(2) = HCO3Calc
CO3(2) = CO3Calc
CO2(2) = CO2Calc
TotPermConc(SP_CO2) = (CO2(5) * CalcPermFlow(1) + CO2(7) * CalcPermFlow(2) +
CO2(9) * CalcPermFlow(3)) / TotPermFlow
CO2toPH Istr(8), Temperature, TotPermConc(SP_HCO3), TotPermConc(SP_CO2),
TotPermConc(SP_CO3)
HPlus(3) = HPlusCalc
HCO3(3) = HCO3Calc
CO3(3) = CO3Calc
CO2(3) = CO2Calc
CO2toPH Istr(9), Temperature, BlendedPermConc(SP_HCO3),
BlendedPermConc(SP_CO2), BlendedPermConc(SP_CO3)
HPlus(10) = HPlusCalc
HCO3(10) = HCO3Calc
CO3(10) = CO3Calc
CO2(10) = CO2Calc


s.Cells(CRow, nCol).Value = HPlus(1)
s.Cells(CRow, Ccol).Value = HPlus(2)
s.Cells(CRow, Pcol).Value = HPlus(3)
s.Cells(CRow, Ccol1).Value = HPlus(4)
s.Cells(CRow, Pcol1).Value = HPlus(5)
s.Cells(CRow, Ccol2).Value = HPlus(6)
s.Cells(CRow, Pcol2).Value = HPlus(7)
```

```
s.Cells(CRow, Ccol3).Value = HPlus(8)
s.Cells(CRow, Pcol3).Value = HPlus(9)
s.Cells(CRow, Bcol).Value = HPlus(10)

' Bicarbonate -HC03
CRow = CRow + 3
i = SP_HCO3
s.Cells(CRow, nCol).Value = HCO3(1)
s.Cells(CRow, Ccol).Value = HCO3(2)
s.Cells(CRow, Pcol).Value = HCO3(3)
s.Cells(CRow, Ccol1).Value = HCO3(4)
s.Cells(CRow, Pcol1).Value = HCO3(5)
s.Cells(CRow, Ccol2).Value = HCO3(6)
s.Cells(CRow, Pcol2).Value = HCO3(7)
s.Cells(CRow, Ccol3).Value = HCO3(8)
s.Cells(CRow, Pcol3).Value = HCO3(9)
s.Cells(CRow, Bcol).Value = HCO3(10)

' Carbon Dioxide - CO2 (calc'd)
CRow = CRow + 1
i = SP_CO2
s.Cells(CRow, nCol).Value = CO2(1)
s.Cells(CRow, Ccol).Value = CO2(2)
s.Cells(CRow, Pcol).Value = CO2(3)
s.Cells(CRow, Ccol1).Value = CO2(4)
s.Cells(CRow, Pcol1).Value = CO2(5)
s.Cells(CRow, Ccol2).Value = CO2(6)
s.Cells(CRow, Pcol2).Value = CO2(7)
s.Cells(CRow, Ccol3).Value = CO2(8)
s.Cells(CRow, Pcol3).Value = CO2(9)
s.Cells(CRow, Bcol).Value = CO2(10)

' Carbonate - CO3 (calc'd)
CRow = CRow + 1
i = SP_CO3
s.Cells(CRow, nCol).Value = CO3(1)
s.Cells(CRow, Ccol).Value = CO3(2)
s.Cells(CRow, Pcol).Value = CO3(3)
s.Cells(CRow, Ccol1).Value = CO3(4)
s.Cells(CRow, Pcol1).Value = CO3(5)
s.Cells(CRow, Ccol2).Value = CO3(6)
s.Cells(CRow, Pcol2).Value = CO3(7)
s.Cells(CRow, Ccol3).Value = CO3(8)
s.Cells(CRow, Pcol3).Value = CO3(9)
s.Cells(CRow, Bcol).Value = CO3(10)

' Bromide -Br
CRow = CRow + 1
i = SP_Br
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
```

```
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
If BlendedPermConc(i) < s.Range("Br2Pass") Then
s.Range("Br2PPower") = 0
s.Range("Br2PPowerMax") = 0
End If
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Chloride -Cl
CRow = CRow + 1
i = SP_Cl
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
If BlendedPermConc(i) < s.Range("Cl2Pass") Then
s.Range("Cl2PPower") = 0
s.Range("Cl2PPowerMax") = 0
End If
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Fluoride -F
CRow = CRow + 1
i = SP_F
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Sulfate -SO4
CRow = CRow + 1
i = SP_SO4
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
```

```
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Nitrate -NO3
CRow = CRow + 1
i = SP_NO3
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Phosphate - PO4 (as PO4)
CRow = CRow + 1
i = SP_PO4
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Hydroxide -OH
CRow = CRow + 1
s.Cells(CRow, nCol).Value = 10 ^ -14 / HPlus(1)
s.Cells(CRow, Ccol).Value = 10 ^ -14 / HPlus(2)
s.Cells(CRow, Pcol).Value = 10 ^ -14 / HPlus(3)
s.Cells(CRow, Ccol1).Value = 10 ^ -14 / HPlus(4)
s.Cells(CRow, Pcol1).Value = 10 ^ -14 / HPlus(5)
s.Cells(CRow, Ccol2).Value = 10 ^ -14 / HPlus(6)
s.Cells(CRow, Pcol2).Value = 10 ^ -14 / HPlus(7)
s.Cells(CRow, Ccol3).Value = 10 ^ -14 / HPlus(8)
s.Cells(CRow, Pcol3).Value = 10 ^ -14 / HPlus(9)
s.Cells(CRow, Bcol).Value = 10 ^ -14 / HPlus(10)

' Silica (as SiO2)
CRow = CRow + 3
```

```
i = SP_SiO2
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' TDS (in ppm)
CRow = CRow + 2

' PH
CRow = CRow + 2
s.Cells(CRow, nCol).Value = Worksheets("Water Quality").Range("pH_input")
s.Cells(CRow, Ccol).Value = -Log(HPlus(2)) / Log(10#)
s.Cells(CRow, Pcol).Value = -Log(HPlus(3)) / Log(10#)
s.Cells(CRow, Ccol1).Value = -Log(HPlus(4)) / Log(10#)
s.Cells(CRow, Pcol1).Value = -Log(HPlus(5)) / Log(10#)
s.Cells(CRow, Ccol2).Value = -Log(HPlus(6)) / Log(10#)
s.Cells(CRow, Pcol2).Value = -Log(HPlus(7)) / Log(10#)
s.Cells(CRow, Ccol3).Value = -Log(HPlus(8)) / Log(10#)
s.Cells(CRow, Pcol3).Value = -Log(HPlus(9)) / Log(10#)
s.Cells(CRow, Bcol).Value = -Log(HPlus(10)) / Log(10#)

' Osmotic Pressure (estimated psi)
CRow = CRow + 1
If NumStages = 1 Then i = 2
If NumStages = 2 Then i = 3
If NumStages = 3 Then i = 4
s.Cells(CRow, nCol).Value = OsmoticPressure(1)
s.Cells(CRow, Ccol).Value = OsmoticPressure(i)
s.Cells(CRow, Pcol).Value = OsmoticPressure(8)
s.Cells(CRow, Bcol).Value = OsmoticPressure(9)
s.Cells(CRow, Ccol1).Value = OsmoticPressure(2)
s.Cells(CRow, Pcol1).Value = OsmoticPressure(5)
s.Cells(CRow, Ccol2).Value = OsmoticPressure(3)
s.Cells(CRow, Pcol2).Value = OsmoticPressure(6)
s.Cells(CRow, Ccol3).Value = OsmoticPressure(4)
s.Cells(CRow, Pcol3).Value = OsmoticPressure(7)

' Ionic Strength
CRow = CRow + 1
s.Cells(CRow, nCol).Value = Istr(1)
s.Cells(CRow, Ccol).Value = Istr(i)
s.Cells(CRow, Pcol).Value = Istr(8)
s.Cells(CRow, Bcol).Value = Istr(9)
s.Cells(CRow, Ccol1).Value = Istr(2)
```

```
s.Cells(CRow, Pcol1).Value = Istr(5)
s.Cells(CRow, Ccol2).Value = Istr(3)
s.Cells(CRow, Pcol2).Value = Istr(6)
s.Cells(CRow, Ccol3).Value = Istr(4)
s.Cells(CRow, Pcol3).Value = Istr(7)

Range("FinalPermTDS") = Worksheets("Water Quality").Range("BlendedTDS")
Range("PrintS1FeedTDS") = Worksheets("Water Quality").Range("FeedTDS")
Range("PrintS1PermTDS") = Worksheets("Water Quality").Range("S1PermTDS")
Range("PrintS1ConcTDS") = Worksheets("Water Quality").Range("S1ConcTDS")
If NumStages > 1 Then
Range("PrintS2FeedTDS") = Worksheets("Water Quality").Range("S1ConcTDS")
Range("PrintS2PermTDS") = Worksheets("Water Quality").Range("S2PermTDS")
Range("PrintS2ConcTDS") = Worksheets("Water Quality").Range("S2ConcTDS")
Else
Range("PrintS2FeedTDS") = 0
Range("PrintS2PermTDS") = 0
Range("PrintS2ConcTDS") = 0
End If
If NumStages > 2 Then
Range("PrintS3FeedTDS") = Worksheets("Water Quality").Range("S2ConcTDS")
Range("PrintS3PermTDS") = Worksheets("Water Quality").Range("S3PermTDS")
Range("PrintS3ConcTDS") = Worksheets("Water Quality").Range("S3ConcTDS")
Else
Range("PrintS3FeedTDS") = 0
Range("PrintS3PermTDS") = 0
Range("PrintS3ConcTDS") = 0
End If
End Sub

Public Sub CO2toPH(ByVal IonStr As Double, ByVal Temperature As Double, ByVal '
' Returns new distrbution of carbonates and new pH based TotalCarbon coming in, CO2,
' HCO3 and CO3 Concentrations
' Carbonate Equilibria data using Stumm and Morgan, Aquatic Chemistry
' pages 120-121 and 148-150
' Linear Regression analysis of Stumm and Morgan data for K1 and K2 versus temperature
' Estimation of Activity Change as Ionic strength from Stumm and Morgan, p 149.
' Inputs are CO2, HCO3, and CO3
' Outputs are pH and new distribution of HCO3 and CO3 to fit new pH

'DEAL WITH ZERO VALUES
If HCO3c = 0 Then
CO3c = 0
CO2c = 0
HPlusCalc = 10 ^ (-7) ' PH SET AT 7
Exit Sub
End If

' first correct K1 and K2 for temperature, using Excel derived equation

pK1 = -0.007 * (Temperature + 273) + 8.4454
```

```
pK2 = -0.0101 * (Temperature + 273) + 13.368

' now correct for ionic strength
pK1 = pK1 - 0.5 * Sqr(IonStr) / (1 + 1.4 * Sqr(IonStr))
pK2 = pK2 - 2 * Sqr(IonStr) / (1 + 1.4 * Sqr(IonStr))

K1 = 10 ^ (-pK1)
K2 = 10 ^ (-pK2)

' First get the total carbon figured out
TotalCarbon = CO3c / 60.0092 + HCO3c / 61.0171 + CO2c / (12.0111 + 2 * 15.9994) ' 2
meqs/mol for CO3, others 1 to 1
If HCO3c <= 0 Then HCO3c = 0.001639 ' minimum 0.1 ppm = .1/61

'Very high pH case
If CO3c / 2 > HCO3c Then ' very high ph ~10.33
HPlusCalc = K2 * HCO3c / (CO3c / 2)
Else ' Do it normally with CO2/HCO3 ratio
HPlusCalc = CO2c / (HCO3c * 0.82 * 10 ^ (6.3))
End If

' Now have the pH, figure out the new distribution of carbonates
' keeping CO2 constant and changing the CO3/HCO3 ratio as needed.
MF_HCO3 = 1 / (HPlusCalc / K1 + 1 + K2 / HPlusCalc) ' Stumm and Morgan, alpha1, p 120
MF_CO3 = 1 / (HPlusCalc ^ 2 / (K1 * K2) + HPlusCalc / K2 + 1)
MF_CO2 = 1 / (1 + K1 / HPlusCalc + (K1 * K2) / HPlusCalc ^ 2)

' now reassign CO2, HCO3, and CO3 based on calculated distrbutions
HCO3Calc = TotalCarbon * MF_HCO3 * 61.0171 ' 1 meq = 1 mmole so no change needed
CO3Calc = TotalCarbon * MF_CO3 * 60.0092 ' 1 meq = 0.5 mmoles or 1 mmole = 2 meq!
CO2Calc = TotalCarbon * MF_CO2 * (12.0111 + 2 * 15.9994)
End Sub
```

Module 1

```
Sub CheckInputs()
'Stop the code if the user needs to revise any inputs
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
Then
If Worksheets("BWRO Flow Balance").Range("NumStages") = 2 Then
If Worksheets("Summary").OptionButton9 = True Then
Ans1 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 1. Do you want to continue?", vbYesNo, "ERROR!!")
If Ans1 = 7 Then
End
End If
End If
If Worksheets("Summary").OptionButton11 = True Then
Ans2 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 1. Do you want to continue?", vbYesNo, "ERROR!!")
```

```
If Ans2 = 7 Then
End
End If
End If
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") = 3 Then
If Worksheets("Summary").OptionButton18 = True Then
If Worksheets("Summary").OptionButton9 = True Or
Worksheets("Summary").OptionButton11 = True Then
Ans3 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 1. Do you want to continue?", vbYesNo, "ERROR!!")
If Ans3 = 7 Then
End
End If
End If
End If
If Worksheets("Summary").OptionButton19 = True Then
If Worksheets("Summary").OptionButton10 = True Or
Worksheets("Summary").OptionButton11 = True Then
Ans3 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 2. Do you want to continue?", vbYesNo, "ERROR!!")
If Ans3 = 7 Then
End
End If
End If
End If
End If
End If

If Worksheets("BWRO Flow Balance").Range("ERDType") = "Turbocharger" Then
If Worksheets("Summary").OptionButton17 = False And
Worksheets("Summary").OptionButton18 = False And
Worksheets("Summary").OptionButton19 = False Then
MsgBox ("Please select where the turbocharger is located before calculating.")
End
End If
End If

If Worksheets("Summary").Range("Recovery") = 0 Then
MsgBox ("Error: Please input the correct system recovery.")
End
End If

If Worksheets("Summary").Range("NVesselsS1") = 0 Then
MsgBox ("Error: Please input the correct number of stage 1 vessels.")
End
End If

If Worksheets("Summary").Range("NumS1Elements") = 0 Then
MsgBox ("Error: Please input the correct number of stage 1 elements.")
End
```

```
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Summary").Range("NVesselsS2") = 0 Then
MsgBox ("Error: Please input the correct number of stage 2 vessels.")
End
End If
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Summary").Range("NumS2Elements") = 0 Then
MsgBox ("Error: Please input the correct number of stage 2 elements.")
End
End If
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
If Worksheets("Summary").Range("NVesselsS3") = 0 Then
MsgBox ("Error: Please input the correct number of stage 3 vessels.")
End
End If
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
If Worksheets("Summary").Range("NumS3Elements") = 0 Then
MsgBox ("Error: Please input the correct number of stage 3 elements.")
End
End If
End If

If Worksheets("Summary").Range("FPEfficiency") <= 0 Then
MsgBox ("Error: Please input a feed pump efficiency in box 7.")
End
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") = 1 Then NVesselsLastStage =
Worksheets("Summary").Range("NVesselsS1")
If Worksheets("BWRO Flow Balance").Range("NumStages") = 2 Then NVesselsLastStage =
Worksheets("Summary").Range("NVesselsS2")
If Worksheets("BWRO Flow Balance").Range("NumStages") = 3 Then NVesselsLastStage =
Worksheets("Summary").Range("NVesselsS3")
If Worksheets("Summary").OptionButton20 = True Then
ConcFlow = (Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("PermFlow")) / 0.003785 / 1440 'm3/d to gpm
Else
ConcFlow = (Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("PermFlow")) / 1440 'gpd to gpm
End If
If ConcFlow / NVesselsLastStage < 10 Then
MsgBox ("Error: Concentrate flow is less than 12 gpm per vessel. Please revise system
design.")
```

```
End
End If

If Worksheets("Summary").OptionButton20 = True Then
If Worksheets("Summary").Range("Flux") > 34 Then
MsgBox ("Error: Flux should be less than 34 lmh.")
End
End If
Else
If Worksheets("Summary").Range("Flux") > 20 Then
MsgBox ("Error: Flux should be less than 20 gfd.")
End
End If
End If

If Worksheets("Summary").OptionButton20 = True Then
If Worksheets("Summary").Range("Flux") < 8 Then
MsgBox ("Error: Flux should be less than 8 lmh.")
End
End If
Else
If Worksheets("Summary").Range("Flux") < 5 Then
MsgBox ("Error: Flux should be greater than 5 gfd.")
End
End If
End If

If Worksheets("Water Quality").Range("Temp_C") > 45 Or Worksheets("Water
Quality").Range("Temp_C") < 2 Then
MsgBox ("Error: Water temperature should be between 2 and 45 degrees C. Please adjust the
temperature on the Water Quality page to continue.")
End
End If

If Worksheets("Water Quality").Range("pH_input") > 10 Or Worksheets("Water
Quality").Range("pH_input") < 2 Then
MsgBox ("Error: Feed water pH should be between 2 and 10. Please adjust the pH on the
Water Quality page to continue.")
End
End If

If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
Then
If Worksheets("BWRO Flow Balance").Range("NumStages") = 1 Then
MsgBox ("Error: There can not be an interstage turbocharger in a 1 stage system. Please
revise configuration.")
End
End If
End If

If Worksheets("Summary").OptionButton24 = True Then
```

```
If Worksheets("Summary").Range("ROBoostPress") = 0 Then
MsgBox ("If you want to include an RO Inlet Booster Pump in the 'System Design' box,
please enter the RO Booster Pump Pressure.")
End
End If
End If

If Worksheets("Summary").OptionButton9 = True Or
Worksheets("Summary").OptionButton11 = True Then
If Worksheets("Summary").Range("BP1Press") = 0 Then
MsgBox ("If you want to include a Booster Pump after Stage 1, please enter the Booster
Pump 1 Boost Pressure in the 'Pressure Control' box.")
End
End If
End If

If Worksheets("Summary").OptionButton10 = True Or
Worksheets("Summary").OptionButton11 = True Then
If Worksheets("Summary").Range("BP2Press") = 0 Then
MsgBox ("If you want to include a Booster Pump after Stage 2, please enter the Booster
Pump 2 Boost Pressure in the 'Pressure Control' box.")
End
End If
End If

If Worksheets("Summary").OptionButton27 = True Then
If Worksheets("Water Quality").Range("FeedTDS") < 20000 Then
MsgBox ("Error: 2nd Pass should only be included for feed water with greater than 20,000
mg/L TDS")
Worksheets("Summary").OptionButton26 = True
End
End If
End If

If Worksheets("Water Quality").Range("FeedTDS") > 10000 Then
If Worksheets("Membrane Database").Range("S1Application") = "BWRO" Then
MsgBox ("Error: A SWRO membrane should be used with this water source. Please decrease
the feed TDS or select a SWRO membrane.")
End
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Membrane Database").Range("L24") = "BWRO" Then
MsgBox ("Error: A SWRO membrane should be used with this water source. Please decrease
the feed TDS or select a SWRO membrane for stage 2.")
End
End If
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
MsgBox ("Error: A SWRO system design can only include 2 stages.")
End
End If
```

```
End If

If Worksheets("Water Quality").Range("FeedTDS") < 3000 Then
If Worksheets("Membrane Database").Range("S1Application") = "SWRO" Then
MsgBox ("Error: A BWRO membrane should be used with this water source. Please increase
the feed TDS or select a BWRO membrane.")
End
End If
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Turbocharger" Then
MsgBox ("Error: Turbocharger upstream of 1st stage membrane is not a typical BWRO ERD
configuration. Please choose a different ERD option.")
End
End If
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Pelton Wheel" Then
MsgBox ("Error: Pelton Wheel ERD is not a typical BWRO configuration. Please choose a
different ERD option.")
End
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Membrane Database").Range("L24") = "SWRO" Then
MsgBox ("Error: A BWRO membrane should be used with this water source. Please increase
the feed TDS or select a BWRO membrane for stage 2.")
End
End If
Else
MsgBox ("Error: A BWRO system design must include a minimum of 2 stages.")
End
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
If Worksheets("Membrane Database").Range("R24") = "SWRO" Then
MsgBox ("Error: A BWRO membrane should be used with this water source. Please increase
the feed TDS or select a BWRO membrane for stage 3.")
End
End If
End If
End If

If Worksheets("Summary").CheckBox2 = True Then
If Worksheets("Water Quality").Range("BypassTDS") = 0 Then
MsgBox ("Error: If there is bypass flow, please enter the desired permeate TDS on the Water
Quality page.")
End
End If
If Worksheets("Water Quality").Range("FeedTDS") > 20000 Then
MsgBox ("Error: Bypass flows are not calculated in this program for feed TDS greater than
20,000 mg/L.")
End
End If
End If
If Worksheets("Summary").OptionButton1 = True Then
'manual projections
```

```
If Worksheets("Summary").Range("S1FeedFlow") = 0 Then
MsgBox ("Error: Please enter in the projections information in the 'Projections Summary'
box.")
End
End If
If Worksheets("Summary").OptionButton15 = True Then 'English units
If Abs((Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("ByFlow")) / 1440 -
Worksheets("Summary").Range("S1FeedFlow")) /
Worksheets("Summary").Range("S1FeedFlow") > 0.1 Then
MsgBox ("Error: Stage 1 Feed Flow in the 'Projections Summary' box should be equal to the
Feed Flow in the 'Flow Information' box.")
End
End If
If Abs((Worksheets("Summary").Range("S1PermFlow") +
Worksheets("Summary").Range("S2PermFlow") +
Worksheets("Summary").Range("S3PermFlow")) * 1440 -
Worksheets("Summary").Range("PermFlow")) /
Worksheets("Summary").Range("PermFlow") > 0.1 Then
MsgBox ("Error: The total permeate flow in the 'Projections Summary' box should be equal
to the Permeate Flow in the 'Flow Information' box.")
End
End If
Else 'Metric units
If Abs((Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("ByFlow")) / 86.4 -
Worksheets("Summary").Range("S1FeedFlow")) /
Worksheets("Summary").Range("S1FeedFlow") > 0.1 Then
MsgBox ("Error: Stage 1 Feed Flow in the 'Projections Summary' box should be equal to the
Feed Flow in the 'Flow Information' box.")
End
End If
End If
If Worksheets("Summary").Range("FeedPress") +
Worksheets("Summary").Range("ROBoostPress") >
Worksheets("Summary").Range("S1FeedPress") Then
MsgBox ("Error: Please enter the correct Stage 1 Feed Pressure.")
End
End If
End If
End Sub
```

APPENDIX D:
Evaluating Long- and Short- Term Planning Under Climate Change Scenarios to Better Assess the Role of Water Reuse

Part I

A Primer for the Water Resource Manager: How to Include Climate Change in *Your* Planning Process

Part I of this report—consisting of Chapters 1 through 8—provides the reader with a short primer on climate change and a simple framework for including climate change in both day-to-day and long-term planning. The climate change planning framework was created based on information collected during our study of three large water and wastewater (W/WW)utilities, the Miami–Dade Water and Sewer Department (MDWASD), the City of Phoenix Water Services Department (PWSD), and the Inland Empire Utilities Agency (IEUA), and is designed to assistwater resource managers as they addresscommon climate change challenges.

Part I is designed to be simple and straightforward, so that it is easy to assimilate and use. Part II (Chapters 9–11) presents our case studies of utilities using the climate change planning framework to provide the reader with both a pragmatic example of the planning framework and a summary overview of thecase studies. Additional technical details are provided in PartIII (Chapters12–20), and the full case studies are presented in Appendices A–C.

Chapter 1

Why Do I Need Guidance?

As a water resource manager or planner you face considerable challenges in planning for the future, even under the best of circumstances. Many of a utility's key planning decisions concern expensive, long-lived investments in water resources, treatment facilities, distribution and collection networks, and other costly infrastructure investments. Many of these high-cost planning decisions with long-term consequences need to be made in the near term, despite uncertainties about future supply, projected demand, regulatory changes, technological advancements, and other parameters that may significantly impact the value of this type of investment over the course of itsuseful asset life.

When the potential impacts associated with climate change are added to the list of planning uncertainties, utility managers can find themselves overwhelmed. This primer is designed to help you, the water resources manager, understand and assess the impacts of climate change on your decision environment *without getting bogged down*. This portion of the report includes a succinct overview of climate change, information on world experts' opinions about the "most likely" changes in precipitation and temperature, tools you can use to identifypotential impacts on your utility that are due to these changes, techniques for identifying which implications are important, ideas for communicating resource management issues raised bychanging climate conditions, and perhaps most important, waysto find and apply adaptive management strategies, including water reuse, to build a flexible utility that can meet the needs of any future.

PartI of this report draws upon knowledge gained during our utility case studies investigating how three large utilities are currently handling the climate change planning challenge: the Miami-Dade Water and Sewer Department (MDWASD), the Inland Empire Utilities Agency (IEUA), and the City of Phoenix Water Services Department (PWSD).The case studies are provided to illustrate both success storiesand how difficult decision-making can be.Although each utility faceddistinctly different climate change challenges, we found that they each had to address the following similar questions:

- What do wereally need to know about climate change/climate variability?
- How and where can weuse what welearn about climate change to make better decisions?
- What changes/adaptations do we need to make to be prepared for potential climate changes?
- What role does reuse play in ourplanning for climate change?
- How do wecommunicate effectively about climate change, given the politically charged nature of the subject?

Figure 1.1 provides a simplified overview of the critical climate-related issues facing each of our case study utilities. We will revisit the case studies throughout this primer to provide specific examples of how utilities address climate change in their planning and management decisions.In addition, this document draws from several previously published papers and case

studies. Links to these and other pertinent papers, as well as a deeper look at several technicalareas overviewed inPart I,are provided in Part III.

Inland Empire Utilities Agency

As a water supply wholesaler and regional wastewater utility, IEUA is faced with unique issues. The biggest is how to ensure that a highly regulated, overused, heavily salted aquifer can continue to meet the growing population needs of southern California without increased use of imported waters. In addition, it must do this with many other players having input.

Miami-Dade Water and Sewer Department

The most critical climate issues faced by MDWASD relate to sea level rise (SLR) and balancing aquifer storage with seasonal stormwater and flood management. The potential impacts of these events are severe. During periods of excessive rainfall or in anticipation of major rainstorms or hurricane landfall, water levels in canals and the water table in the Biscayne aquifer are lowered to increase stormwater storage capacity. The key issue in stormwater and flood management is how to manage these aquifer water levels. It is important to strike a balance between the need to keep the aquifer's stormwater capacity available during wet periods andthe need to store freshwater for higher demandperiod that occurs during the potentially drier seasons. New regulations, which ban ocean outfalls and preserve groundwater flows to the Everglades, are also creating planning complications.

City of Phoenix Water Services Department

PWSD is currently working to address future water supply reliability within the context of climate change and other uncertainties. Key decisions and investments PWSD is making and/or faces in the nearterm include developing a new drought and shortage management plan and planning for the development of additional long-term supply sources. In terms of both drought and supply planning, the city's core focus is adequacy and affordability of "shortage insurance" to maintain lifestyles and the economy.

Figure 1.1.Critical planning issues faced by the case study utilities.

Chapter 2

How Will This Guidance Help Me?

We hope this guidance will help you identify the when, where, and how of including climate change in your day-to-day decisionmaking. Every day you consider practical issues such as what size pipe to install, how big your reservoir needs to be, or how much to invest inconservation efforts. For some of these decisions, particularly the long-term, expensive, and effectively irreversible kind—such assizing future water storage systems—you need to consider how climate change may impact the decisions. For less consequentialdecisions—such aswhich pumps to install in your pumping station—it probably isnot necessary to address potential climate change impacts.

Climate change is a big subject full of unknowns and probabilities.Our goal is to help you focus on what you can include in your planning so you donot get bogged down in what you donot know for sure.Figure 2.1 provides an overview of the elements that need to be included/identified when you includeclimate change in your planning. Each of these ingredients is discussed in more detail in later chapters.

It is important to recognize right from the start that although you need to include information about each element in your planning, you will not be able to identify specific "amounts" for most of these items.That is, although you want to include likely changes in precipitation and temperature, you will not be able to say, definitely, that temperatures will increase in summer months by 3°F by 2040.You are more likely to be able to say that temperatures are likely to increase by 3 to 5°F in June, July, and August by 2040–2060, temperatures in May and September are likely to increase by 2 to 4°F by 2050, and winter month temperatures are likely to increase less until 2080.

This guidance is designed to show you where to access information about each ingredient and how to use that information appropriately. We discuss tools and techniques to ensure that the unknowns and probabilities donot cause your plan to fail, whatever the future brings. And although we discuss ways to use large computer models to identify impacts and perform decision support, the focus of thisprimer is on how to use easily available information to make good resource management decisions today that include potential changes in climate in the future.The goal of Part I is to provide you with sufficient information to include all the ingredients outlined in Figure 2.1 in your planning, easily and with an understanding of the consequences of the unknowns involved.

In addition, this document is designed to help you identify where and how climate change may expand the need for and value of water reuse as an adaptation strategy. Water reuse is typically envisioned as a means of supplementing potable water supplies. The uncertainties surrounding climate change, however, demand a new flexibility in meeting water supply objectives, as well as complementary objectives that could be threatened by climate change. These additional objectives include in-stream flow augmentation, wetland creation or enhancement, coastal groundwater injection for saltwater intrusion barriers, fire suppression and control, agricultural irrigation, wastewater management, and groundwater replenishment. For all these objectives, water reuse is a viable engineering and management technique.

Element #1: Temperature and precipitation

Identify the most likely changes in precipitation and temperature for your utility location

Element #2: Impacts and implications

Identify the direct impacts/implications for your utility of the identified changes in temperature and precipitation

Element #3: Risks and vulnerabilities

Assess/identify the risks and vulnerabilities associated with the identified direct impacts of climate change

Element #4: Adaptation/preparation

Prepare for highly likely and high consequence risks and vulnerabilities by identifying adaptation strategies—including reuse

Element #5: Coordination and communication

Identify other important players; establish agreements for sharing risks and maximizing flexibility

Figure 2.1. Elements of a climate change planning framework for utilities.

But before we look at how climate change may affectthese issues, and raise others, let us look at what scientists know about climate change.

Chapter 3

What Do I Really Need to Know About Climate Change?

Fora water resource manager who needs to communicate information about climate, it is important to be familiar with at least the basics of climate change science, the world players in the discussion of climate change and their statements, and the probable impacts on temperature, precipitation, hydrology, and related environments that are due to climate change. This chapter provides a very basic overview of climate science and who is involved.

3.1 Basic Climate Science

Climate science looks at the complex relationship among the atmosphere, the oceans, land surfaces and ice, solar radiation, the Earth's orbit, greenhouse gas (GHG) emissions, pollution, and multiple other factors that affect our planet's climate.Note that these relationships impact the overall climate,which in turn affects weather patterns. Because these relationships are so complex, it requires enormous computer models to simulate what happens when one input is changed (such asGHG emissions). These models are known as global climate models (GCMs).Most climate change predictions are based on GCM results, and are developed by combining the outputs from 23 of the world's most respected GCMs. Basically, GCMs simulate the impacts on climate if GHG emissions rates increase rapidly over thiscentury, or if GHG emissions decrease orincrease more slowly over time. A summary of the GHG scenarios definedby the Intergovernmental Panel on Climate Change (IPCC) is provided in Figure 3.1. A complete description of the GHG scenarios is provided in Chapter 12. Note that the IPCC states that "All (scenarios) should be considered equally sound" (IPCC, 2007b).

Fora water resource manager it is particularly important to understand the basic science concerning how climate change is predicted to impact the water cycle. The basic science of how heat trapped in the atmosphere affects the water cycle differently given different landforms is illustrated in Figure 3.2. It is important to note that heat trapped by the atmosphere results in more evaporation and more precipitation, leading to more extreme precipitation events.

3.2 Who Are the Important Climate Change Players?

The Intergovernmental Panel on Climate Change (IPCC), established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988, is recognized as the world leader on climate change. The role of the IPCC is to assess—on a comprehensive, objective, open, and transparent basis—the scientific, technical, and socioeconomic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts, and options for adaptation and mitigation. The IPCC does not carry out research nor does it monitor climate-related data or other relevant parameters. It bases its assessment mainly on peer-reviewed and published scientific/technical literature.

Scenario A1:	The A1 scenario family describes a future world of very rapid economic growth, global population that peaks in midcentury and declines thereafter, and the rapid introduction of new and more efficient technologies.
Scenario A2:	The A2 scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities.
Scenario B1:	The B1 scenario family describes a convergent world with the same global population as in the A1 storyline,which peaks in midcentury and declines thereafter, but with rapid change in economic structures toward a service and information economy. The emphasis is on global solutions without additional climate initiatives.
Scenario B2:	The B2 scenario family describes a world in which the emphasis is on local solutions to sustainability. It is a world with continuously increasing global population, at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. The scenario is also oriented toward environmental protection and social equity, and focuses on local and regional levels.

Figure 3.1.Summary of GHG emission scenarios.

Source: IPCC (2007b).

The IPCC is an interdisciplinary and intergovernmental body composed of 194 participating countries.It mobilizes scientific experts from around the world to carry out assessments of global climate science based on the available relevant literature. Thousands of scientists from all over the world contribute to the IPCC reports.The members of the IPCC Bureau, including the IPCC chair, serve in their expert capacity and are not paid by the IPCC. Rigorous review is an essential part of the process, broadening the set of individual contributions and ensuring an objective and comprehensive assessment of current information.

For the IPCC Fourth Assessment Report, released in 2007, 559 experts from 130 countries served as lead authors.More than 2500 reviewers provided more than 90,000 comments. With the release of its Fourth Assessment Report, *Climate Change 2007: Synthesis Report*, the IPCC removed many doubts that had previously shrouded both scientific and policy discussions of climate change. This came about because mounting evidence made the situation much clearer to scientists and government policy analysts from all over the world who participated in a six-year process to arrive at the consensus presented in the report.

The two overall summary statements that captured world attention from the report were as follows (IPCC, 2007a):

1. Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases.
2. A global assessment of data since 1970 has shown it is likely that anthropogenic warming has had a discernible influence on many physical and biological systems.

Now that you know what the world authority states, without doubt—that natural systems are already being affected—the next step is to identify what the experts think will be the impacts of these changes on hydrologic systems.

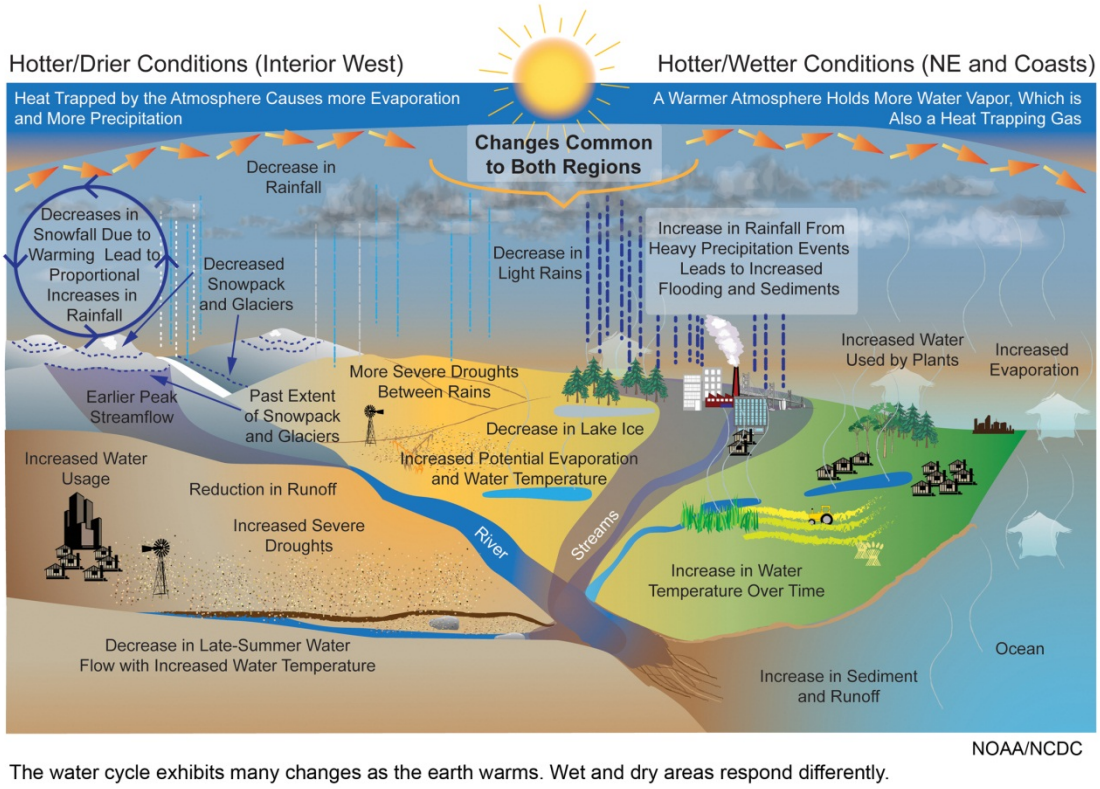


Figure 3.2.Overview of projected changes in the water cycle.
Source: Karl et al. (2009, p. 42).

3.3 What Do We Know with High Confidence About Climate Change?

The IPCC's Fourth Assessment Report states with "high confidence" that the following effects are currently occurring:

- Increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers
- Warming of lakes and rivers in many regions, with effects on thermal structure and water quality

In the future, the IPCC experts predict that the following will occur:

- By midcentury, annual average river runoff and water availability are projected to increase by 10–40% at high latitudes and in some wet tropical areas, and to decrease by 10–30% over some dry regions at midlatitudes and in the dry tropics, some of which are currently water-stressed areas. In some places and in particular seasons, changes will differ from these annual figures.
- Drought-affected areas will likely increase in extent. Heavy precipitation events, which are very likely to increase in frequency, will augment flood risk.
- Overthe course of the century, water supplies stored in glaciers and snow cover are projected to decline, reducing water availability in regions supplied by melt water

from major mountain ranges, where more than one-sixth of the world's population currently lives.

- Coasts are projected to be exposed to increasing risks, including coastal erosion, because of climate change and sea level rise (SLR) (averaging 0.2 to 0.8 meters by 2100 and possibly worse).

The IPCC summary is taken from the *Journal of the American Water Works Association* article "No Doubt about Climate Change and Its Implications for Water Suppliers" (Cromwell et al., 2007).

3.4 Can You Be More Specific About What Is Known About Changes in Temperature and Precipitation in the United States and My Region?

In 2009, the United States Global Climate Research Group (USGCRG) (Karl et al., 2009) presented summaries of the projected regional impacts of climate change within the United States. Projections were provided for both temperature and precipitation. Karl et al. stated that as a general pattern, changes in temperature projected for the mid- to late 21st century extend the regional trends and patterns of change already observed through the 20th century, as illustrated in Figure 3.3.

By late in the 21st century, temperatures are projected to increase by between 4.0 and 6.5 °F if a low greenhouse gasemissions pathway is assumed, and between 7and 11 °F if a high-emissions pathway is assumed. Warming is expected to be greatest at higher latitudes and in midcontinental areas such as the Great Plains and Great Basin. Warming will be more moderate in coastal areas, including western Washington, Oregon, and California, and in the coastal Southeast. A color graphic illustration of projected increases in temperature for the United States can be found in "Global Climate Change Impacts in the United States"(available at http://globalchange.gov/publications/reports/scientific-assessments/us-impacts,p. 34).

Patterns of precipitation in the mid- to late 21st century are projected with somewhat less confidence than temperature projections, although many recently identified trends are anticipated to continue through the coming century. As a general trend, northern areas of the United States will become wetter and southern areas drier. Parts of the Southwest, in particular, are projected to become even drier in coming decades.

One key to remember when interpreting regional forecasts is that mean annual precipitation levels are less important for water supply management than changes in precipitation patterns, including the intensity of precipitation, the number of dry days between precipitation events, and the likelihood of rain rather than snow.Figure 3.4 illustrates one of the most important changes occurring in precipitation—the changes in magnitude of precipitation events.

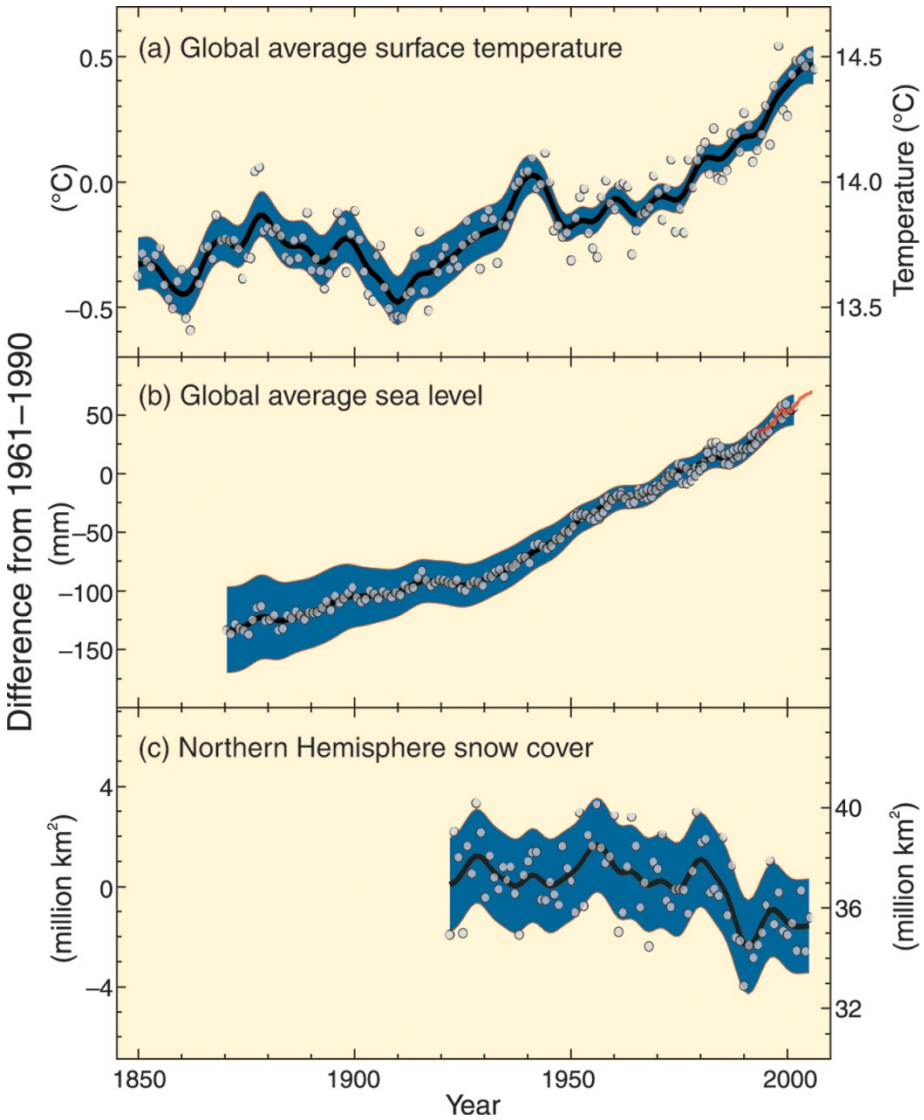


Figure 3.3.Observed changes in temperature, sea level rise, and snow cover.
Source: IPCC (2007a, Figure 1-1).

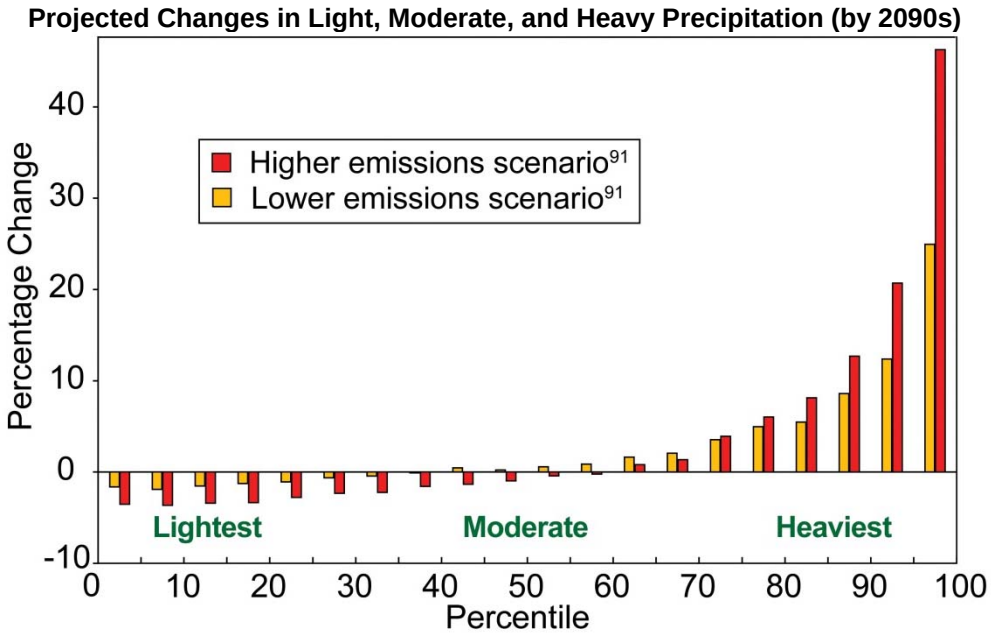


Figure 3.4.Observed changes in precipitation intensity.

*Note:*The figure shows projected changes from the 1990s average to the 2090s average in the amount of precipitation falling in light, moderate, and heavy events in North America. Projected changes are displayed in 5% increments from the lightest drizzles to the heaviest downpours. As shown here, the lightest precipitation is projected to decrease, whereas the heaviest will increase, continuing the observed trend. The higher-emission scenario[91] yields larger changes. Projections are based on the models used in the IPCC 2007 Fourth Assessment Report.

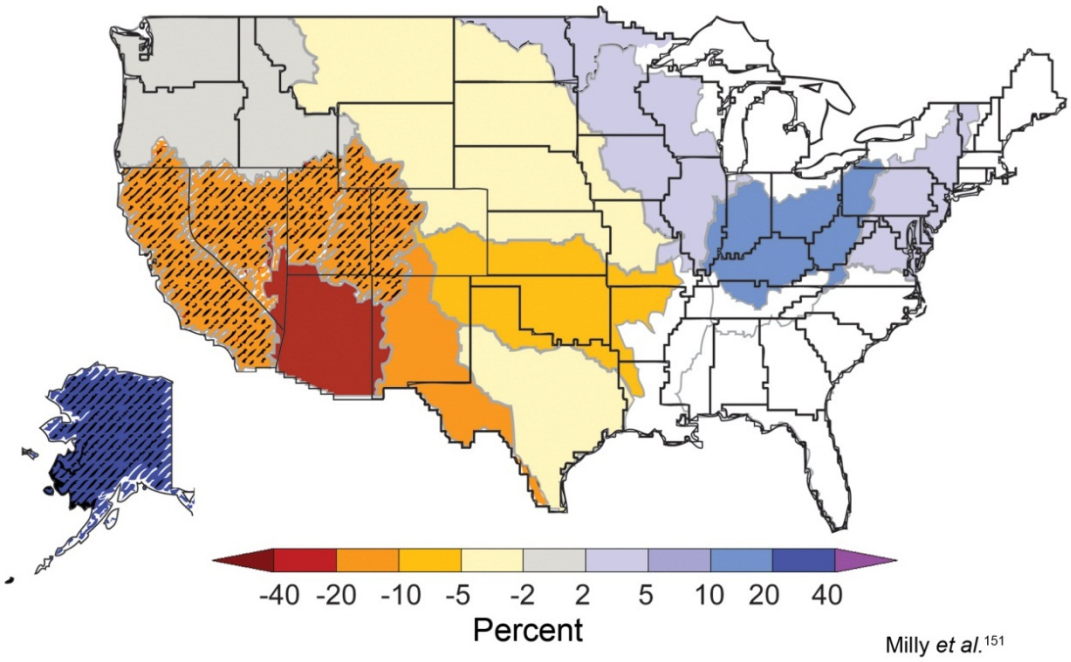
Source: Karl et al. (2009, p. 32).

The results of this projected change in the magnitude of precipitation events are illustrated in Figure 3.5, predicted for changes in runoff.For you, as a water resource manager, this is an importanttake-home message.

Another technique for identifying local changes in temperature and precipitation is to downscale the information developed in the large global climate models (GCMs) to a specific location.A discussion on how to downscale data is provided in Chapter 6 and in greater detail in Chapters12 and 13.

3.5 IsThis Enough Information to Identify High-Probability Changes in Precipitation and Temperature for Your Utility?

It may be possible to identify high-probability changes in precipitation and temperature. But remember these caveats: confidence in winter and spring projections is generally higher than that in summer and fall projections. In addition, these projections highlight the strong north–south pattern of variation. One area of particular uncertaintyis how climate change will affect summer monsoon patterns, which can have a significant impact on summer (and hence total annual) precipitation in the southwestern United States (e.g., Phoenix). In general, there is uncertainty about how thunderstorms will be affected, which could dramatically change summer rainfall patterns. And remember, these projections are based on outputs of large-scale GCM simulation models, and the weaknesses or uncertainties associated with these models are reflected in the projections.



Runoff, which accumulates as streamflow, is the amount of precipitation that is not evaporated, stored as snow pack or soil moisture, or filtered down to groundwater. Projected changes in median runoff for 2041-2060, relative to a 1901-1970 baseline, are mapped by water-resource region. Colors indicate percentage changes in runoff. Hatched areas indicate greater confidence due to strong agreement among model projections. White areas indicate divergence among model projections. Results are based on emissions in between the lower and higher emissions scenarios.[91]

Figure 3.5.Projected changes in annual runoff that is due to climate change.

Source: USGCRP, 2011b.

Chapter 14 in Part III, High Probability Climate Changes, provides additional maps and data for many regions of the nation. However, in a nutshell, Figure 3.6 provides a summary of what is known as of early 2012 with a high degree of confidence about the regional impacts of climate change.This information will contribute significantly to addressing Element 1 and we hope that you will post this chart of what is known about climate change, with a high degree of confidence, and consider the implications of these potential changes when making long-term decisions.

We started thischapter by stating that as a water resource manager you need to know the basics of climate change so that you can communicate effectively with your various stakeholders.Although we devote an entire chapter (Chapter 8) to climate change communication (including how to keep from getting bogged down in the politics), before leaving this section, we want to suggest that in many cases it is not necessary to mention global warming or even climate change. As a resource manager, your goal ofgood resource management requires you to plan for all probable changes, including climate change. However, as a good communicator, it is sometimes easier for you to discuss options in terms of prudent planning, climate variability, and other reasons for the decision in order to keep the discussion focused on resource management and away from preconceived ideas about climate change.

Changes in the Mountain West

- Warmer and shorter winter seasons
- Warmer and potentially drier summer seasons
- More intense rainfall events

Changes in the Southwest

- Warmer and probably drier overall
- More extreme droughts
- More extreme heat waves
- More intense rainfall events
- Vegetation changes

Changes in the humid East, Southeast (except coastal areas), and Midwest

- Warmer overall
- Possible increases in annual precipitation
- More intense rainfall events

Changes in coastal regions

- Rising sea levels
- Warmer overall
- More intense rainfall events
- More intense storm events
- More extreme heat waves
- More dry spells and extreme droughts

Figure 3.6.Summary of highly likely changes in climate by region during the next century.

Chapter 4

What Are the Direct Implications of High-Probability Changes in Climate for My Utility?

In the last chapter we identified probable changes in temperature and precipitation in the world, the United States, and U.S. regions.Although identifying anticipated changes is interesting, it is more important that you identify the direct impacts or *implications foryour utility* of the projected changes in temperature and precipitation.In this chapter we provide two tools you can use to identify the potential effects of climate change on your water utility functions and operations.

It is important to note before we begin the discussion of utility implications of climate change that the evaluation of impacts needs to include both the chain of causation and the timing (e.g., more intense rainfall events may lead to flooding, which may lead to increases in turbidity, which may lead to changes in treatment processes by 2060).Figure 4.1 illustrates this causation link.

It is important to remember when reviewing the likely impacts on water utilities that other factors besides climate change will continue to impact your utility.For example, flooding will be affected by changes in peak precipitation events, winter precipitation levels, and snowmelt, as well as land use changes unrelated to climate change.

4.1 Climate Change Implications Tool #1: Causation Checklists by Region

The first tool for identifying how changes in temperature and precipitation will impact your utility is presented in Figure 4.2. This example of a Regional Climate Causation Listgroups potential changes in temperature and precipitation into categories.In this example, for the Mountain West, three categories are presented: Warmer and shorter winter seasons, Warmer and potentially drier summer seasons, and More intense rainfall events. The Climate Causation checklist then provides a summary of potential changes for each category. For example, under the category “Warmer and shorter winter seasons,” the identified potential changes include “More rain, more rain-on-snow, and earlier spring snowmelt.” A list is then presented that identifies the potential implications of that specific climate change for utilities. To continue our example, the implicationsof “More rain, more rain-on-snow, and earlier spring snowmelt” include “Altered recharge of groundwater aquifers, earlier runoff into surface waters, and lower summer/fall base flows in surface waters.” The Regional Causation Checklists can be an excellent tool for ensuring that you identify all the potential implications of climate change for your utility.

Additional checklists are provided in Part III, Chapter 15.

Expected future climate changes

- Higher temperatures
  - Larger increases in summer than winter
- Likely changes in *seasonal* precipitation
  - *Annual average* precipitation, regionally: +/-?
  - Summers likely to see less rainfall
  - More dry days between rainfall events
- More intense precipitation events
- Potential for more extreme droughts
- Stresses on watershed and recharge areas
- Sea level rise

➔

Likely impacts on water utilities

- Implications from source to tap:
  - Watershed changes
  - Treatment challenges
  - Distribution impacts
  - User demands
- Impacts include risks to
  - Water quantity
  - Water quality
  - Facilities and supporting infrastructure

Figure 4.1. Basic climate change impacts we believe are likely to occur with a relatively high degree of confidence and the likely utility vulnerabilities.

Category 1: Warmer and shorter winter seasons

*Climate change impact:*More rain, more rain-on-snow, and earlier spring snowmelt

Utility implications

- Altered recharge of groundwater aquifers
- Earlier runoff into surface waters
  - Lower summer/fall base flows in surface waters

Category 2:Warmer and potentially drier summer seasons

Climate change impact: Changes in vegetation of watershed and aquifer recharge areas

Utility implications

- Altered recharge of groundwater aquifers
- Altered quantity and quality of runoff into surface waters [e.g., total organic carbon (TOC), alkalinity]
- Changes to vegetation from fire and pests

*Climate change impact:*Increased water temperature

Utility implications

- Increased evaporation and eutrophication in surface sources
- Water treatment and distribution challenges (e.g., disinfection, byproducts, regrowth)

*Climate change impact:*Increased water demand

Utility implications

- Increased irrigation demand in longer growing season
- Increased urban demand with more heat waves and dry spells
- Increased drawdown of local groundwater resources to meet the previous

Category 3:More intense rainfall events

*Climate change impact:*Increased turbidity and sedimentation

Utility implications

- Loss of reservoir storage
  - Shallower, warmer water; increased evaporation and eutrophication
  - Potential conflicts with flood control objectives
- Water filtration or filtration/avoidance treatment challenges

Climate change impact: Increased risk of flooding

Utility implications

- Increased risk of direct flood damage to water utility facilities

Figure 4.2.Climate causation checklist for the Mountain West.

4.2 Climate Change Implications Tool #2: The Cromwell Flow Charts

The second tool we provide for ensuring that you identify all potential implications of climate change for your utility is the Cromwell flow chart. Because climate change implications for water resource management are multifaceted, flow diagrams, an example of which can be found in Figure 4.3, were created to clarify all of the steps. These diagrams track the possible impacts of climate change, such as increasing temperatures. Even far-reaching secondary hydrologic and environmental effects are examined and potential areas of concern identified. This deconstruction of the problem provides a good overview of the full scope of the problem and a convenient means of organizing information. Additional flow charts are provided in Part III, Chapter 15. The Cromwell flow charts can be used in a manner similar to the Causation Checklists.

4.3 Is This Enough Information to Identify the Direct Impacts/Implications of the Identified Climate Changes in Temperature and Precipitation for Your Utility?

The two tools presented in this chapter are designed to ensure that no cause and effect impact is neglected; but they are only tools and need to be used by knowledgeable personnel to be usefully interpreted.You will need to consider the unique circumstances of your utility carefully when using them. As a simple take-away message, Figure 4.4 provides the U.S. Global Change Research Program's(USGCRP's) summary of the future impacts of climate change on water resources.

In the next chapter we discuss how to use this information to ensure that climate change impacts are considered, to the best of your ability, in both your current day-to-day water resource management decisions and your long-term planning.

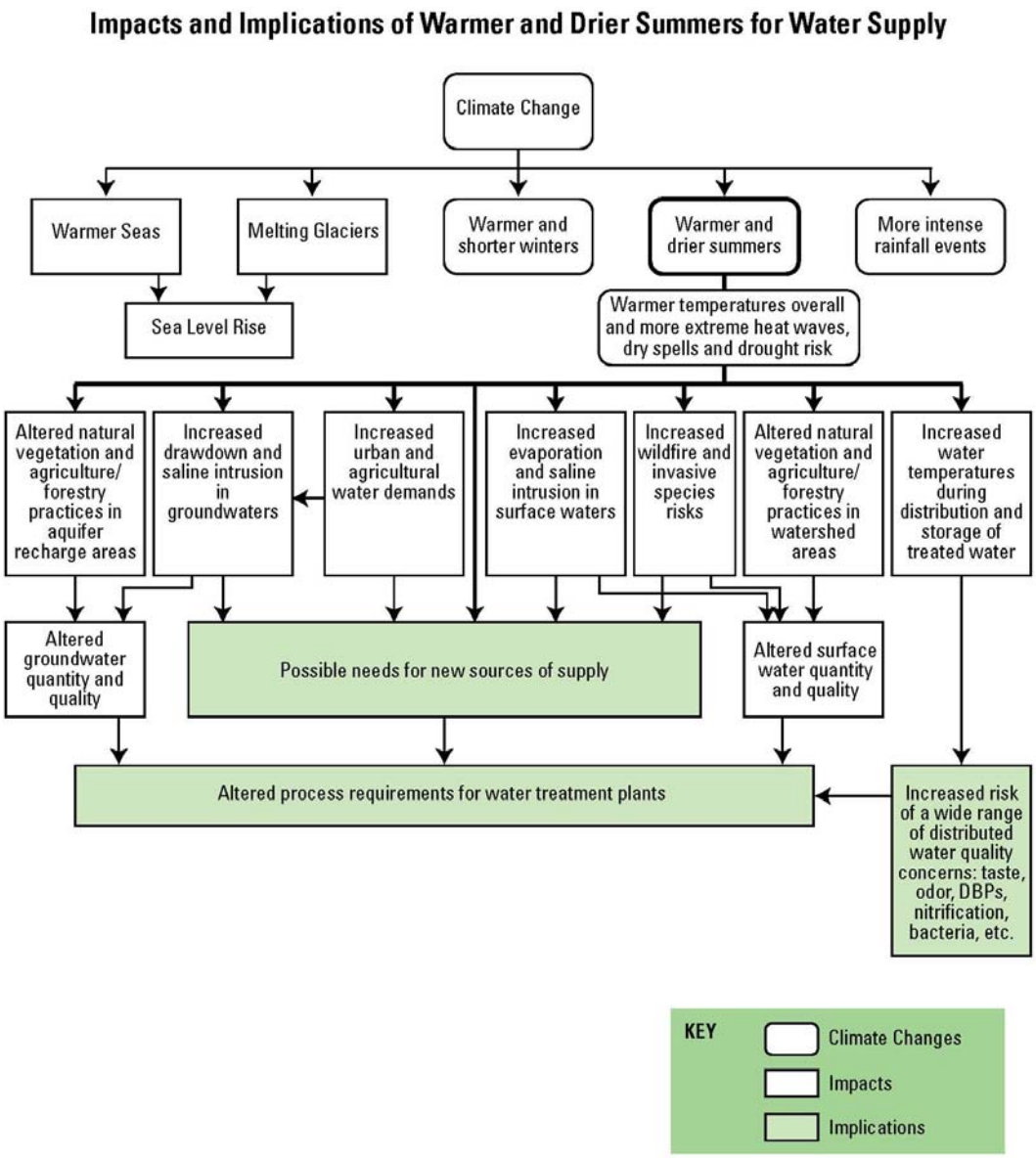


Figure 4.3. Impacts and implications of warmer and shorter winters for water supply agencies.

*Source:*Cromwell et al., 2008.

The water cycle

Climate change has already altered, and will continue to alter, the water cycle, affecting where, when, and how much water is available for all uses.

Floods and droughts

Floods and droughts are likely to become more common and more intense as regional and seasonal precipitation patterns change, and rainfall becomes more concentrated in heavy events (with longer, hotter dry periods in between).

Precipitation and runoff

Precipitation and runoff are likely to increase in the Northeast and Midwest in winter and spring, and decrease in the West, especially the Southwest, in spring and summer.

Snowpack

In areas where snowpack dominates, the timing of runoff will continue to shift to earlier in the spring and flows will be lower in late summer.

Water quality

Surface water quality and groundwater quantity will be affected by a changing climate.

Treatment systems

Climate change will place additional burdens on already stressed water systems.

Historical record planning

The past century is no longer a reasonable guide to the future for water management.

Figure 4.4. High-probability impacts of climate change on future water resources.

Source: USGCRP, 2011a.

Chapter 5

How Do I Determine Which of the Impacts of Climate Change to Be Worried About?

In this chapter and the next we discuss several ways of including the information you develop about climate change impacts into your decision-making. The first two approaches are often referred to as bottom-up techniques, as they use what you already know about your entire system—such as supply sources, infrastructure, and demand.The third approach, presented in Chapter 6, discusses how to use sophisticated computer modeling and includes a discussion on how to downscale data from GCMs. This is often referred to as a top-down approach.

The first approachto selecting impacts of concern for your utility identifies tipping points and areas of vulnerability that may be further stressed by changes in climate. The second approach uses a risk matrix to identify which of the potential climate impacts are likely to result in high-probability and/or high-consequence events.It is at this juncture that we begin our discussion about the role of reuse in planning for and preparing for climate change.

5.1 Identifying Tipping Points: A Bottom-Up Approach for Including Climate Change in Your Utility Decision-Making

A tipping point analysis is used to identify where the climate change impacts you identified previously may be enough to change a decision.The tipping point analysis relies upon your knowledge of your utility's systems and circumstances to identify key thresholds, or "tipping points," that would create problems for your system or that might alter a major upcoming decision. For example, if you are assessing your future supply source portfolio, you already understand what reservoir inflow level would tip you into a likely water shortage situation. In a tipping point analysis, you might identify that the change in future reservoir inflows that is due to less precipitation in the form of snowpack could result in water supply shortages for your service area, and mightbe large enough to tip the decision to include a new source such as water reuse (a climate-independent supply source) in your planning.

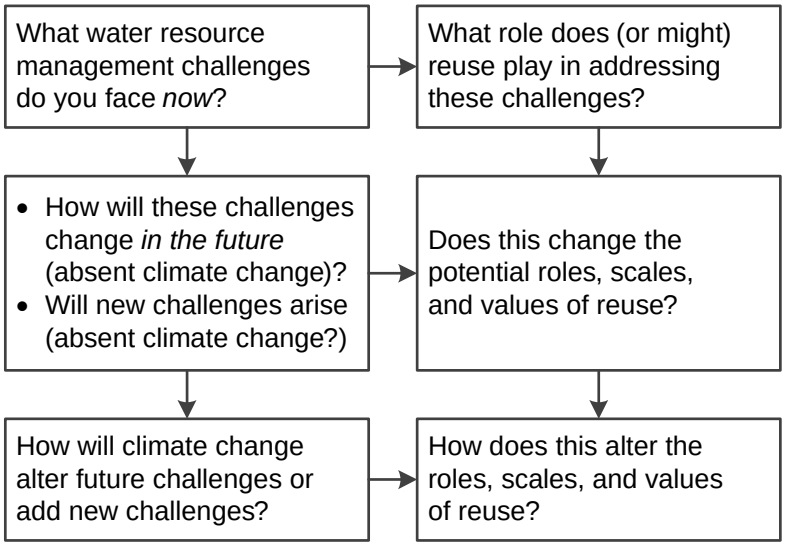
The tipping point approach, and how reuse fits into this approach, is summarized in Figure 5.1.

A tipping point analysis begins by identifying what you and other utility managers and planners already know best:

- How your utility is set up (e.g., existing and planned treatment systems, available water supply options, key storage levels, water demands, regulatory constraints)
- Existing or anticipated water resource management challenges you currently recognize and are trying to address (e.g., periodic water supply shortfalls, the vulnerability and cost of your imported supplies [if any], increasingly stringent total maximum daily limits regulations that may increase wastewater treatment costs [making water reuse less costly at the margin and, thus, more financially feasible])

- Major decisions you plan to make over the coming years, especially any long-lived and expensive investments that may be influenced by climate change (e.g., infrastructure investments in treatment plants, distribution or collection systems, storage facilities, and water supply development)

Figure 5.1.Overview of tipping point approach.



Next, factor in what you have identified about climate change.Include both highly probable changes in temperature and precipitation and the implications of those changes for your utility. Address how these implications affect each of the current water resource management challenges and major future decisions your utility faces. By looking at the existing water or wastewater and related water resource management challenges, and then adding the likelihood of climate change scenarios and impacts, you gain useful insight into where and how water reuse and other adaptations can help you deal with future climate change impacts. For example, in New Hampshire, more extreme rainfall events are occurring already. Field engineers have found that culverts no longer provide an adequate flow rate and so have begun lining them with noncorrugated liners, effectively increasing flow by up to 15%.

An example of identifying a tipping point might be as follows: suppose you have a sense that summer temperatures would need to increase by 10 °F or more by 2060for you to re-rank your preferred treatment plant upgrade alternatives. If readily available climate change model projections tend to indicate that by 2060 temperatures in your region will increase from 3 to 8 °F, then you have a clear answer. You donot need to know exactly where within the projected temperature range the “best” projection lies. Instead, you know with some confidence that it is highly unlikely that the temperature increase will exceed your tipping point.

Alternatively, if the range of projections includes your tipping point (e.g., if your tipping point is about 5°F and the range of projected change is from 3 to 8 °F), then you need to do a bit more work. You may need to get some expert guidance on the likelihood (probability) of

exceeding the tipping point. Or you may need to use your own judgment and analyze the consequences (downside risk) you face under alternative temperature levels. This becomes a matter of decision-making under uncertainty. A further discussion of decision-making tools is provided in Chapter 17. Ideally you can make choices that guide you in a way that leaves options open for later consideration and adjustment (this is known as "adaptive management"). For example, if your climate change projections leave you uncertain about whether you will need a new reservoir or not, purchasing the land upon which you may someday build the reservoir leaves your options open. An example of how Miami–Dade used the tipping point approach is provided in Figure 5.2.

5.2 Identifying High-Risk High-Consequence Issues Using a Risk Profiling Matrix

Risk management analysis provides another technique for identifying where climate change impacts may have significant implications for your utility, and therefore which ones you need to worry about.But before we begin our discussion of risk, let us make sure we are all on the same page.Figure 5.3 provides a series of risk-related definitions. Based on these definitions, we can see that the techniques presented in Chapters 4 and 5 are actually risk identification and risk assessment techniques, respectively. Risk management, or climate change adaptation/preparation, is discussed in Chapter 7.The rest of this chapter focuses on how to use risk analysis to characterize your utility's risks associated with climate change.

The Miami-Dade utility (MDWSD) found that probable climate changes may represent a tipping point in its decision to add a reclaimed water aquifer storage and retrieval (ASR) program

MDWSD will need to comply with a recently enacted State of Florida mandate that bans coastal wastewater discharge by 2025. The utility, which currently discharges wastewater to the ocean, will need to find a way to discharge or use its treated wastewater effluent in some inland context. The mandate requires the district to reuse 60% of its wastewater volume; the balance may be discharged as wastewater. This will largely entail deep well injection into a highly saline formation 3000 feet below the surface.

This regulatory mandate is independent of climate change. Add climate change, associated SLR, and increased storm surge to the picture, and it is clear that there is a potentially valuable opportunity for water reuse to meet the growing need for seawater intrusion barriers to protect the sole source aquifer serving the region.

Figure 5.2. Climate change adds to regulatory pressures to promote valuable reuse options.

Risk identification

Recognizing and understanding how climate is changing, and may change further in future decades (generally on a global scale and with an annual/seasonal time step).

Risk assessment

Identifying how climate change will impact the environments (natural/social) within which water utilities operate (e.g., less summer precipitation, reduced streamflows) on a utility-relevant geographic scale (e.g., watershed, service area) and time step (e.g., monthly, daily).

Risk characterization

Building from the prior risk identification and assessment steps to form a vulnerability assessment of how the projected potential changes in W/WW utility operating environments will pose risks to utilities (i.e., raising the probabilities and/or consequences of adverse outcomes). The vulnerability assessment is based on a cross-cutting evaluation of

- Risks arising from source to tap (including watersheds, storage, treatment, distribution, and user demands)
- Risks posed to water quality, water quantity, and infrastructure (including "secondary effect" risks such as population migration or pest infestation)

Risk management

Identifying, evaluating, selecting, and implementing adaptation strategies (e.g., reuse) to increase resiliency and retain/add flexibility, using approaches such as adaptive management, "no regrets" (or "low regrets"), and "green infrastructure."

Figure 5.3.Risk framework definitions.

Risk characterization, or vulnerability assessment, is useful in helping you prioritize risks and determine the issuesthat require you to gather more information.As a simple example, assume Utility A has identified Warmer and Drier Summers as a potential impact of climate change. Using the portion of the Cromwell flow charts illustrating the implications of warmer and drier summers for water supply (shown in Chapter 4, Figure 4.3), Utility A can be relatively sure they have assessed/identified all the risks associated with warmer and drier summers. They now need to characterize these risks in order to sort out which risks are important and which ones are not as big a deal for them. Characterizing the risk is accomplished by adding two pieces of information–the consequences and the likelihood of the impact–to each identified risk. Figure 5.4 illustrates how Utility A has characterized one identified risk associated with climate change, *increased drawdown and saline intrusion in groundwaters.*

To take this example further, Figure 5.5 provides a risk matrix for more than one potential climate change impact for Utility A. You can see from these two examples that as the number of risks being characterized increases, the ability to easily draw inferences from a simple list decreases. Figure 5.6 illustrates the power of the risk matrix graphic, both as an analytic and as a communication tool. By utilizing the risk matrix, Utility A can easily identify the climate change impacts that are either highly likely and/or have high consequences.

In this example of a risk matrix framework it is clear that Utility A does not need to put much effort into considering how to prepare for/adapt to impacts A2 and C2 and probably not B2, either. However, B1 should be a priority and A1 and C1 should definitely be on the "prepare for" list.Note that if you identify any risk with catastrophic consequences, such as a Category 5 hurricane, you should still spend some time considering the implications regardless of the likelihood..

Risk to Utility A:Increased drawdown and saline intrusion in groundwaters

Likelihood: Highly likely for this utility based on regional hydrology

Consequence A1:
Altered groundwater quantity and quality represent major consequences for this utility, as more than 60% of its supply is from groundwater

Consequence A2:
Possible need for new supply sources represents a major consequence for this utility, as additional supply sources are extremely expensive

Consequence A3:
Altered process requirements for water treatment plants (WTPs) represents an insignificant consequence for this utility, as the current treatment facility is adequate for all likely new sources

Figure 5.4.Characterizing one risk for Utility Athat is due to climate change.

Chapter 16 in Part III provides additional details on risk frameworks and examples of how to use them.

5.3 Is This Enough Information to Identify Risks and Vulnerabilities?

By using the techniques outlined, you can identify the high-consequence and/or high-probability risks of climate changefor your utility and have a good idea of which ones your utility should be worrying about.In the next chapter we look at ways to use large computer modeling to accomplish the same goals. Then, in Chapter 7, we get to the really important stuff—identifyingpotential options for adapting to/preparing for your identified areas of concern, with a special emphasis on how reuse can provide a resilient, climate-independent supply source.

Risks associated with warmer and drier summers

Risk A:*Altered groundwater quality and quantity*

Risk A1: *Increased drawdown and saline intrusion in groundwaters*

Likelihood: Possible to likely based on regional hydrology
Consequence of RiskA1: Major to catastrophic (groundwater is sole source)

Risk A2*: Altered process requirements for water treatment plants*
Likelihood: Possible to likely
Consequenceof Risk A2: Insignificant to low, as current treatment can handle projected changes

Risks associated with warmer and shorter winters

Risk B:*More rain and less snow*

Risk B1: *Water supply—altered recharge of groundwater aquifers*

Likelihood: Almost certain
Consequence of Risk B1: Major to catastrophic (groundwater is sole source); possible need for new supply(consider reuse, a climate independent source)

Risk B2: *Wastewater—altered biology and chemistry of receiving waters*

Likelihood: Almost certain
Consequence of Risk B2: Low to minor, as treatment can handle projected changes

Risks associated with more intense rainfall events

Risk C: *Altered groundwater quantity and quality*

Risk C1: *Water supply—altered natural vegetation in groundwater recharge areas*

Likelihood: Possible to likely
Consequence of Risk C1: Major to catastrophic (groundwater is sole source); possible need for new supply(consider reuse, a climate independent source)

Risk C2: *Stormwater—altered biology, chemistry, and geomorphology of receiving waters*

Likelihood: Possible to likely
Consequence of Risk C2: Low to minor, as current treatment facilities can handle projected changes

Figure 5.5.Characterization of risks for a series of climate change implications for Utility A.

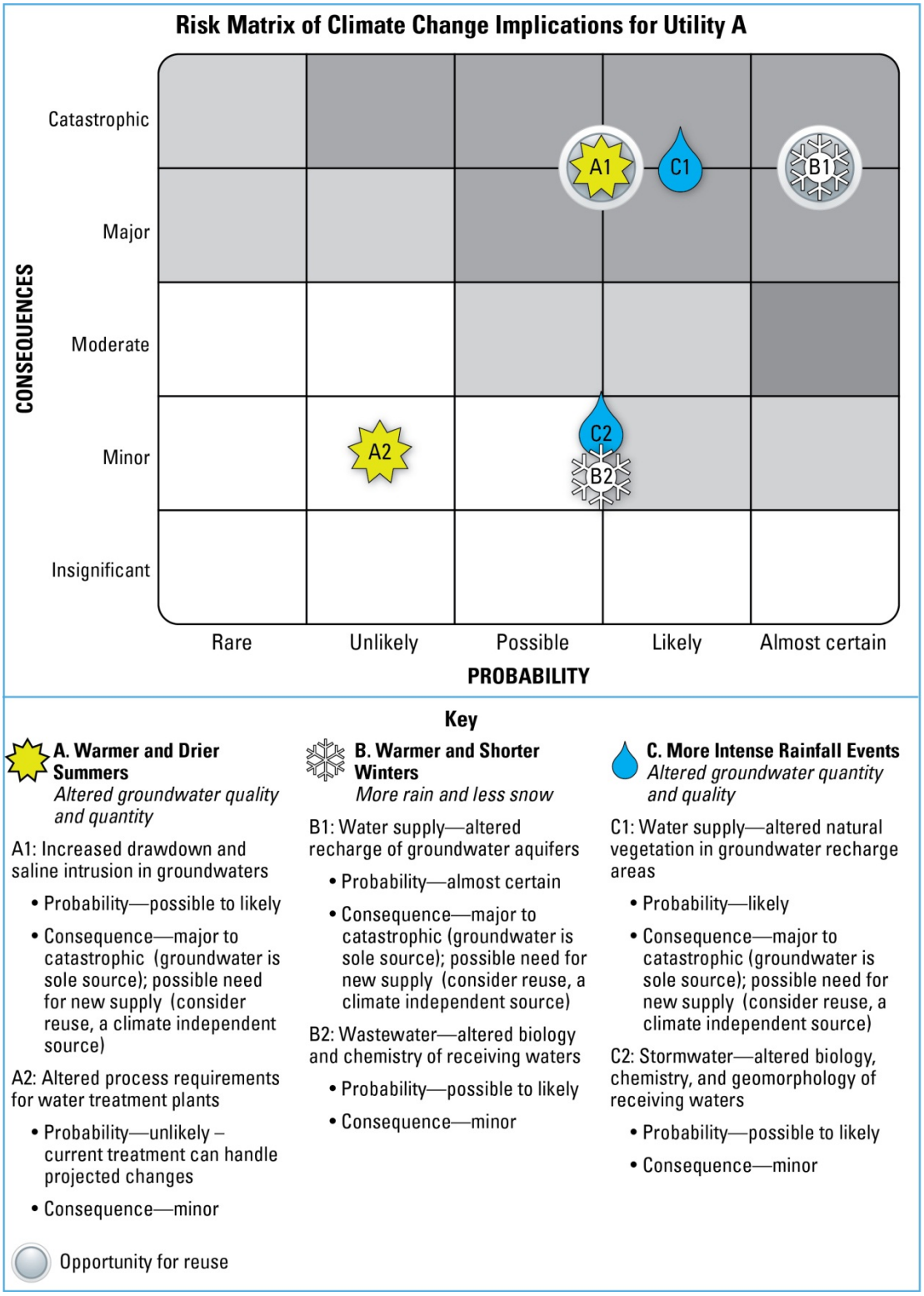


Figure 5.6.Risk matrix of climate change implications for Utility A.

Chapter 6

How Do I Use and Understand Computer Models in Climate Change Planning?

In the last few chapters we looked at techniques for using readily available information to identify implications of climate change for your utility and where your utility may have a tipping point or vulnerability to climate change.In this chapter we look at how utilities can use large computer model outputs for the same purposes.

There are two situations in which,as a water resource manager, you may need to understand how a large, multilevel modeling effort can be used to address climate change impacts:if the utility undertakes a large modeling effort itself,and if as the resource manager you are asked to review a model and interpret the results. This chapter provides a succinct overview designed to get you started in either situation. Part III, Chapters 12 and 13,provides a more in-depth discussion of computer modeling, as well as links to other resources.

Regardless of whether the utility is considering undertaking a top-down modeling effort to identify climate change impacts or isreviewing amodel that provides relevant information, it is vital that as the resource manager you understand the model inputs and outputs, as well as what question the model is designed to answer. In this chapter we identify the different types of models often included in a climate change analysis and identify issues that can affect the reliability of the outputs.

Figure 6.1 illustrates a typical chain of models and the inputs and outputs for a model-centric, top-down approach to looking at climate change impacts on utilities. In this example there are actually four different computer models. The first is the global climate model (GCM), the second is the downscaling model designed to take the large-scale changes in precipitation and temperature identified in the GCMs and make the results more site specific, the thirdis the hydrologic model that looks at the implications of the temperature and precipitation changes forwater supplies, and finally comes the decision support model that can help utilize the developed information in your planning efforts.Note that a subset of the data output from each computer analysis provides the input for the next model run. As a model is only as good as its inputs, it is vital that you be as familiar as possible with how and why the inputs were selected and the implications of these choices.

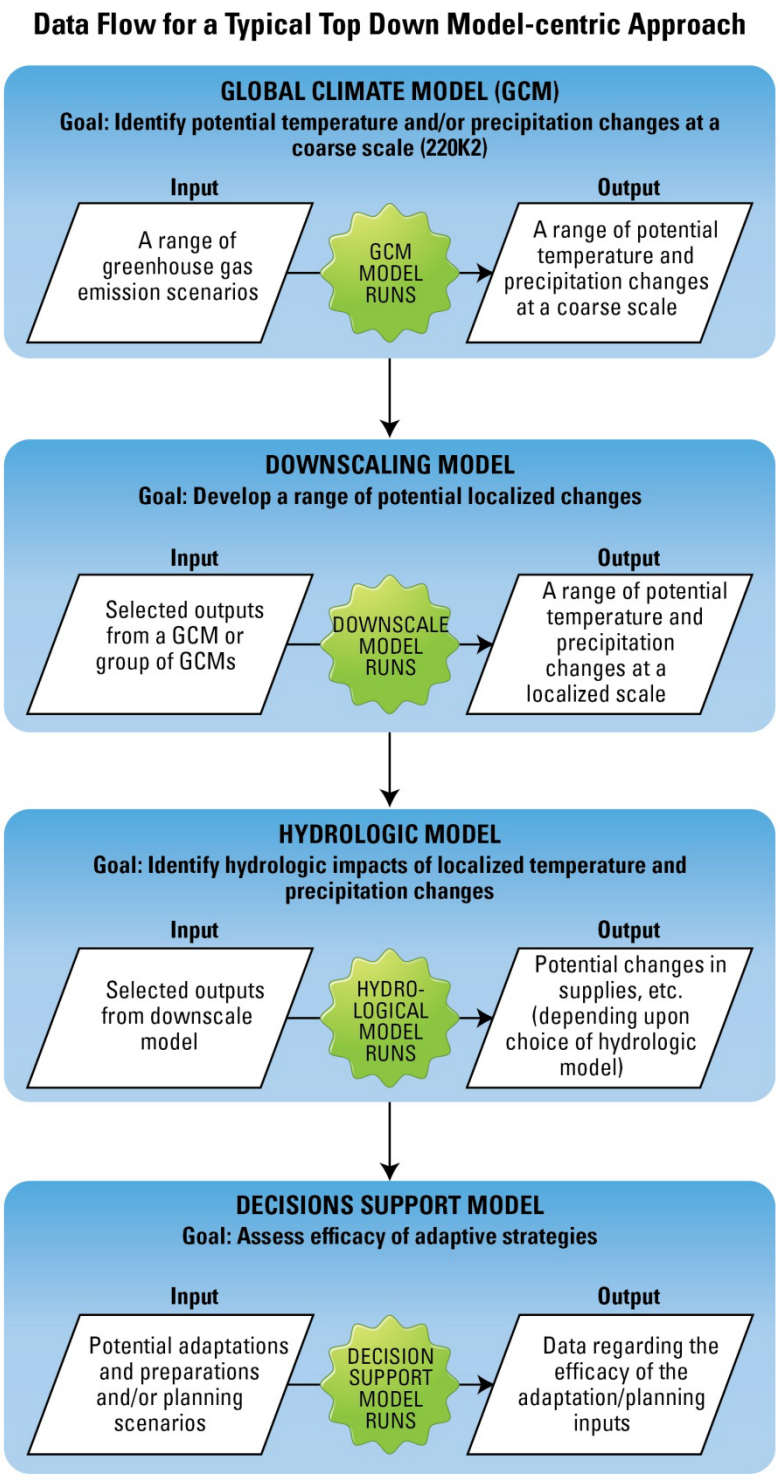


Figure 6.1. Data flow for a typical top-down model-centric approach.

6.1 Global Climate Models

A top-down model-centricapproach to including climate change in your planning begins with a look at large global climate models (GCMs).GCMs simulate the complex relationship among the atmosphere, oceans, land surfaces and ice, solar radiation, the Earth's orbit, greenhouse gas (GHG)emissions, pollution, and many other factors that affect our planet's climate.GCMs use a variety of potential GHG emissions scenarios as inputs. Some use conservative estimates of future GHGs that assume carbon emissions are reduced (known as green scenarios) and others simulate what will happen if no changes or increases in carbon emissions occur. (A discussion of GHG scenarios is provided in Chapters 3 and 12.) Typically, results across several GCMs and GHG emissions scenarios are used to create a range (or develop an average) of potential changes in temperature and precipitation on a large geographic scale for a specific time scale (e.g., changes in temperature for North America from 2060 to 2090).The typical grid size for a GCM is 200 km × 200 km (about 120 miles × 120 miles). Utilities typically take the output from completed GCMs and do not necessarily run these large-scale models themselves because they are very expensive, complicated, and time-consuming to run.

What utilities need to understand about GCMs is which GCM, or group of GCMs, was used, theemissions scenario used as input, and the time scale selected. Specifically, consider if the GCMs model high or low carbon emissions in the future.This is important because if the input for your selected GCM represents a very green scenario (e.g., all nations have significantly reduced carbon emissions), then the rest of your modeling will represent green scenarios.Also, is the time period being modeled the time period you are considering? If you are planning for 2030 and the GCM model runs project outcomes for 2060, then that model output is not likely to be useful to you.

A further discussion of GCM inputs and outputs is provided in Part III, Chapter 12.

6.2 Downscaling

Once GCM output is sorted and relevant data are selected, the next step is to identify data relevant toyour utility's location, such as a watershed or service-area scale. In some cases the data from a GCM or group of GCMs areadequate for your needs.However, GCMs do not pick up the small-scale variations in climate that are typically seen in coastal and mountainous areas or other locations with unique geomorphology.In these cases, downscaling can be a useful technique, as itcan often be used to simulate these small-scale changes.

To provide this more useful level of resolution, GCM outputs can be downscaled via one of three basic approaches: (1) simple downscaling, (2) statistical downscaling, or (3) dynamic downscaling. Before further discussion of downscaling, it is important to point out a few key concerns.First, if the GCM does not accurately project changes in climate (and of course this is an unknown), then the downscaling options will not improve the projections. This is why many experts choose to use an assemblage of GCMs instead of just one; an assemblage has been shown to be significantly more accurate (IPCC, 2007a). Second, it is a common misconception that increasing the resolution of climate projections will increase their accuracy. This is not true. In fact, by adding an additional analytical or modeling layer to the GCMs, the downscaled results can have a higher (compounded) level of uncertainty. Monsoon, La Niña, and similar types of weather events are not represented in either GCMs or downscaling models, and can have significant impacts on the reliability/usefulness of the

outcomes. Nevertheless, the higher-resolution output from downscaling GCMs can be very useful if applied appropriately and with sufficient attention to uncertainty.

Downscaling is often used to address the question, "Do the large-scale changes in temperature and precipitation that came out of the GCMs apply to the area of interest to my utility?" When a downscaling technique is used to answer this question, be sure to understand the following:

- How was downscaling *input* selected and how will this impact the downscaling?For example, if only worst-case scenario GCMs are used, then all downscaled data will also represent only worst-case scenarios (a full discussion of GCMs is presented in Part III, Chapter 12).
- What downscaling *technique* was used and how does that choice affect the outputs? See Chapter 13 in Part III for further discussion of this issue.
- What time scale was selected? What was the past reference point and the future projection point? Is this appropriate for the decision being considered? Historical references can be from one year, an average of years, or a series of years—the same for the future. If you are interested in a 20-year planning horizon, then projections for 100 years may not prove useful.
- Do you have an important geographical (local mountains) or weather pattern feature (e.g., monsoon, La Niña) that is not well captured by the model? What effect does this have on the results?

Chapter 13 in Part III provides more details on how to access and interpret downscaled data.

6.3 Hydrologic Modeling and Decision Support Modeling

Once data have been downscaled and you have developed a set of highly likely changes in climate, the next step is to see if you can identify potential changes in hydrology. Hydrologic computer models are used to see how the changes in temperature and precipitation will impact the hydrology of the area. This is another way to look at the implications of the changes for your utility.

The final modeling step illustrated in Figure 6.1 is a decision support model.Decision support models are designed to take complex information and determine how it affects decisions.Simple decision support models include benefit–cost analysis and financial bottom line analysis.A more detailed discussion of decision support models is provided in Part III, Chapter 17.

6.4 An Example of Applying Climate Change Models to an Utility

It may help you to understand climate modeling by looking at how the Inland Empire Utilities Agency (IEUA) used computer modeling to assist in their climate change assessments.IEUA, a large organization with lots of data, had two prestigious organizations—the University of California at Davis Center for Environmental and Water Resources Engineering and the RAND Institute—complete large climate-change-related modeling exercises for them. Each model posed a different question and therefore took a different angle.The University of California used the CALVIN (California Value Integrated Network) model to look at "the economic performance and physical feasibility of a wide variety of water management

activities" for the State of California (Medellín-Azuara et al., 2008) and the RAND study, "Preparing for an Uncertain Future Climate in the Inland Empire," asked, "What are the vulnerabilities related to climate change in IEUA's long-term water plans and what are the most effective options for managing these risks?"(RAND, 2008).

6.4.1 GCM Selection for IEUA

Both organizations began by selecting GCM inputs. The CALVIN modelers, Medellín-Azuara et al. (2008), used a warm-dry form of climate change as input. RAND modelers used an assemblage of model forecastsderived from 21 different GCMs with a middle-of-the-road emissions forecast. Each forecast was weighted by its ability to reproduce past climate data and level of agreement with other forecasts (Tebaldi et al., 2006).

6.4.2 Downscaling to the IEUA Area

The CALVIN modelers downscaled the selected global dataset using the downscaling model that is sometimes referred to as the Maurer dataset to develop more geographically relevant data. The Maurer dataset develops climate change ratios for monthly precipitation and temperature databy comparing the GCM downscaled monthly averages for the 30-year time periods of 1965–1994 and 2070–2099 (Maurer et al., 2007).The Maurer downscaling approach calibrates the accuracy of the model by looking at the model's ability to predict historical data.

The downscaled ratios developed for California indicate a decrease in the magnitude of precipitation, an earlier snowmelt, and stream flows increasing slightly in January and February but decreasing in all other months. These ratios were applied to historical surface water flows to produce a new climate time series.

RAND worked with David Yates of the National Center for Atmospheric Research (NCAR) to downscale the GCM data to develop weather projections for the IEUA service area (Yates et al., 2003).[1] RAND assumed that the driest precipitation projections correspond to the warmest temperature projections. Most climate models suggest that strong warming will deepen persistent drought in the subtropical region, and the IEUA area is at the northern edge of this regional boundary. This effect suggests a strong negative relationship between temperature and precipitation. However, if El Niño conditions are disproportionately strengthened as warming trends continue (which has a high probability), then the region could experience warmer temperatures and more tropical storms (Tebaldi et al., 2006).

RAND found that by assuming that the GCMs are valid representations of future climate dynamics, it is possible to create a range of predicted temperature and precipitation changes throughout Southern California. According to the model outputs, the likely range (±1 standard deviation of the mean projected increase) of the average summertime temperature increase is projected to be between 0.1 °C and 2.1 °C. The likely range of average wintertime precipitation trends is between a 19% decrease and an 8% increase (RAND, 2008).

[1]The K-nn downscaling technique applied for this purpose uses a statistical representation of historical daily weather so that the resulting sequences retain the basic statistical character of the historical data but also include a specific new trend.

6.4.3 Hydrologic Models Applied to the IEUA Region

The CALVIN hydrological model looks at the entire interconnected California water system (including surface water and groundwater with more than 1200 spatial elements, 51 surface reservoirs, 28 groundwater links, 600+ conveyance links, more than 85% of the currently irrigated area, and 90% of the population). Climate-warming scenarios are imposed as hydrological inputs in the CALVIN network, which uses the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM). A public domain linear network flow optimization solver, developed by the U.S. Army Corps of Engineers (USACOE; Draper et al., 2003), is employed to provide a prescription of monthly water allocation in space and time for the California water system over a 72-year time period as a CALVIN output. Climate-altered hydrologic inflows and reservoir evaporation for more than 150 locations in California's water supply system were estimated using the permutation ratio method to alter the 72-year monthly unimpaired historically based flow record following the methods presented by Zhu et al. (2005). This approach preserves the interannual variability of the hydrologic system and also incorporates changes in seasonal patterns and volumetric totals.

RAND imported the climate scenarios generated in Steps 1 and 2 into the Water Evaluation and Planning Model (WEAP), which was developed by the Stockholm Environment Institute. WEAP is based on a set of supply and demand relationships represented by nodes. The nodes represent IEUA catchments, indoor-demand sectors, surface supplies, and groundwater basins. Rivers, conveyance facilities, and other flows link the nodes.

Step 3 was the last modeling step for the CALVIN model, although repeated for each climate scenario analyzed. The CALVIN model is an optimization model designed to look at the optimum water supply distribution as measured by total costs, including water scarcity and operating costs. The set of CALVIN model runs account for the effects of changes in population growth and land use, including changes in agricultural and urbanization patterns through different hydrological scenarios and historical and one or more forms of climate change in California.

The CALVIN modelers concluded that for the state of California, "Compared with the historic hydrology, optimized operations for the dry climate warming scenario raise water scarcity and total operation costs by $490 million/year with year 2050 demands. Actual costs might be somewhat higher where non-economic objectives prevail in water management (e.g., instream ecological needs)" (Medellín-Azuara et al., 2008). For the Inland Empire, CALVIN concludes that it is not economically optimal to rely on increases in water supplies from the State Water Project (SWP) forfuture needs, becauselimitations in the state conveyance system may limit the ability to deliver additional water supplies to Southern California.

The RAND study focused on the bottom modeling level, Decision Support Modeling. A discussion of its findings is included in the discussion of decision support tools (DSTs) presented in Chapter 17.

Chapter 7

How Do I Ensure That My Utility Is Prepared for the Impact of Climate Change?

And What Role Does Reuse Play in Preparing for Climate Change?

Now that you have developed a basic understanding of climate change science, identified potential changes in temperature and precipitation and their implications for your utility, and identified the specific issues that represent significant risks, vulnerabilities, and tipping points, the next step is to figure out how you can adapt or prepare your utility without spending money you donot have and/or end up preparing for a future that doesnot happen. Although this sounds daunting, it is what a water resource manager does every day—plan for an uncertain future.

This chapter addresses this vital issue by identifying the components of an effective overall climate change adaptation/preparation strategy that are applicable regardless of autility's specific climate challenges. Although examples of specific adaptation ideas are also provided, the specific preparations you will need to make will be unique to your utility.Also, as we suggested initially, water reuse is a key player on the preparation/adaptation playing field.

7.1 Definition of an Adaptive PreparationStrategy

Let us start by defining what we mean by an adaptive response. A good adaptive response reduces your system's vulnerability and improves its resilience. This can take the form of reducing the odds (probability) that you will suffer a large negative impact, reducing the severity (consequences) of a negative impact, and/or improving the ability of your utility to bounce back and recover from a negative event.If you had unlimited funds, you could develop adaptive responses to all the climate change impacts you have identified.But because you donot, you have to choose wisely and be vigilant. Your previous work identifying the highly likely, high-consequence impacts will help ensure that this doesnot happen.

In general, a strategy that prepares your utility for the impacts of climate change, and all the other uncertainties regarding the future::

1. Promotes flexibility and efficiency
2. Considers options for diversifying the supply portfolio, includingclimate-independent sources— such as reuse and desalination
3. Practices integrated water resource management
4. Identifies areas for collaboration—it improves the odds of accomplishing items 1–3

Each of these climate preparation strategies is discussed in more detail in the remainder of this chapter.

7.2 Promote Greater Flexibility and Efficiencies

One of the most effective ways to prepare for climate change is to develop utility flexibility and efficiency.This strategy includes

- *Implementing no-regrets options*—options that make good sense under the existing climate and also make sense if climate does change. For example, if initiating a reclaimed water program makes financial sense today, it represents a no-regrets climate change option;that is, it also provides a climate-independent supply source that will prepare the utility for climate change.
- *Modifying actions over time*, when feasible, to allow circumstances and impacts to become more clear. For example, if your utility is likely to require an additional reservoir under climate change it may make sense to purchase the land today, keeping options open, but wait for further development until climate impacts are clearer.
- *Postponing or modifying irreversible investments* on expensive and long-lived assets that may be climate-change vulnerable, when feasible. For example, if your water treatment facility will need updating in the next 10 to 15 years, it may make sense, if possible, to wait until the end of that period to see how new climate change information affects the decision (e.g., about scale and/or types of treatment processes).
- *Monitoring key parameters* to determine if and when you are approaching a key tipping point so that you can act if and when necessary with suitable adaptations. For example, if the tipping point for the need for a new reclaimed water program is a reduction in groundwater recharge of 3% and climate change in 2020 is projected to decrease recharge by 2.5%, this is a parameter you will want to keep close tabs on.
- *Enhancing conservation and leak reduction programs*. Decreasing demand is an excellent strategy when supply sources are projected to decrease.
- *Increasing the number of water supply options* available (discussed as a separate strategy).
- *Identifying decentralized and hybrid approaches* to water/wastewater management, *including reclaimed water* (discussed separately).
- *Providing redundancies* (where doing so is costeffective). For example, creating a reclaimed water program provides opportunities for backup supplies.
- *Using market-based mechanisms* to support valuable reallocation of water resources. For example, using water markets to acquire or transfer water rights.

The highlighted words in this list represent adaptive words to live by!

7.3 Diversify Water Supply Sources

Climate change has a high probability of impacting a large variety of supply sources because, for example, ofthe impact of warmer and shorter winters on natural vegetation and agriculture/forestry in aquifer recharge areas, more rain and less snow, more rain on snow, earlier snow melt and runoff, altered recharge of groundwater aquifers, altered aquifer levels and safe yield from groundwater sources, altered summer and fall base flows in surface

water, and lower reservoir levels and less safe yield from surface sources.An excellent way to prepare for these changes is to diversify supply sources.Diversifying supply sources will decrease your overall vulnerability to climate change by spreading the risk.

Options for diversifying your portfolio of water supply sources include the following:

- Add or expand water reuse! Including
  - Collecting and using storm water
  - Reclaiming wastewater
  - Injecting partially treated water in aquifers
- Add or expand desalination
- Enhance conservation and leak reduction programs
- Add groundwater to a surface water-dependent system
- Add surface water to a groundwater-dependent system
- Provide redundancies (where costeffective to do so).
- Water trading and options

For example, the yields from water reuse and desalination are generally insensitive to drought conditions, so they are less likely to be impacted by climate change, whereas in most western states surface water sources are likely to be impacted by climate change. The addition of reuse or desalination to your portfolio reduces the extent to which droughts will impact your overall supplies. Diversification of your supply portfolio is typically a no-regrets option, making good sense regardless of whether, or how, climate changes. An example of how this unexpectedly made a noticeable difference in Australia is shownin Figure 7.1.

Given the expected impacts that climate change will have on water resources, reliance on a single source of supply may become an increasing risk for many water utilities. Existing water intake systems may not be adequate under climate change, and the foreseeable increasing cost of water that is available for treatment and distribution may force utilities to assess alternative options. This may include building new reservoirs or expanding the capacity of existing reservoirs; tapping groundwater aquifers; creating opportunities for interbasin water transfers; capturing unharnessed resources (e.g., harvesting storm water); implementing desalination; or employing water reuse technologies. Later in this chapter we demonstrate several ways that water reuse can fit into portfolio diversification and other adaptation strategies.

7.4 Promote Integrated Water Resource Management

Practicing integrated water resource management means taking a broad and holistic view of all your water and wastewater (W/WW) resources and challenges. For example, it may entail viewing wastewater as a resource that can be used to address some of your region's water supply needs.

Practicing integrated water resource management also implies considering the interaction of land use planning and management with your water resource issues. The quality of water resources and land use are intrinsically linked. Land type and use, andhuman intervention (along with natural and climatic factors), will have a strong influence on receiving waters. Land use management helps utilities protect water quality, which can be impacted by soil

erosion, land salinity, agrochemicals from farmlands, industrial pollutants, or runoff with high levels of silt.

An Australian desalplant built for drought provides emergency water supplies during heavy flooding

From the late 1990s through 2009, much of Australia was experiencing extreme drought conditions. Traditional water supplies and reservoir storage were greatly diminished, and austere water use restrictions were put in place in most of the nation. In response to the severity and duration of this drought, many parts of Australia proceeded to aggressively develop alternative supplies such as coastal desalination and water reuse. A desalination facility was developed along the Gold Coast (the central portion of Australia's eastern shore, just south of Brisbane) as part of this aggressive effort to develop alternative and drought-resistant water supplies.

Then, after years of drought, the weather patterns shifted dramatically and transformed into a two-year period of unusually large rainfall events. It seemed thatthe drought was history, and critics of the desalination facility began to express consternation over bearing the high cost of building an energy-intensive desalination facility that was now looking like an unnecessary, stranded asset. However, as the wet weather pattern continued and intensified, the region suffered flooding of previously unknown proportions. The flooding incapacitated some of the region's traditional surface water treatment plants (WTPs). Suddenly, the coastal desalination facility became a critical asset, providing potable water when other supply options were forced offline.

The message is that it is valuable to diversify your water supply portfolio, regardless of what types and levels of climate risk and uncertainty you are facing. Although the desalination facility was built as a remedy to the extended drought, it turned out to provide considerable value to the community ina completely different and unanticipated set of circumstances. Diversified supply portfolios can thus add value by giving options in the face of anticipated risk.

Figure 7.1. The value of supply diversification: Desalination on Australia's Gold Coast.

For example, activities on agricultural land, forests, and fallow and pastureland affect watershed soils and vegetation, which in turn impacts non-pointsource pollution runoff, water infiltration, and so forth. Likewise, factors such as urbanization, shifting cultivation, mining, and industrialization within watersheds directly influence the quality of water from surface runoff. Also, as temperatures increase, so will algae blooms and associated turbidity issues.

Examples of integrated water resource management practices include the following:

- Enhance storage capacity (e.g., aquifer storage, surface reservoirs; see example in Figure 7.2)
- Protect your source water (e.g., watershed protection)
- Use green infrastructure to enhance infiltration and reduce runoff
- View your wastewater as a resource (e.g., consider adding to water reuse)
- Replenish groundwater (e.g., aquifer replenishment)
- Monitor for key climate change impacts (related to your tipping points)

Seasonal needs may prevent aquifer replenishment from being a year-round element of a reclaimed water program for MDWASD

Infiltration into the Biscayne aquifer system is extremely important for flood and stormwater control during the rainy season, when large rainfall events often occur. For this reason, aquifer levels must be kept low enough in rainy months to accommodate this infiltration and provide adequate storage capacity to mitigate downstream flooding. Lowering the aquifer levels for flood control must be carefully balanced with the need to store as much water as possible in the aquifer to meet the community's need during dry periods. The implication for MDWASD is that using reclaimed water for aquifer replenishment may not be a viable strategy in wet periods, because there is a need to keep aquifer storage capacity available for storage of rainy season runoff. This seasonality of water reuse applicabilityfor aquifer replenishment creates an impediment to reuse options.

Figure 7.2. Miami-Dade example of managing Biscayne aquifer levels across seasons.

To manage water effectively and promote better watershed/source water protection, municipalities and water utilities will have to extend their operational reach to include watershed vegetation and ecology. To facilitate this, better communication and coordination within water utilities and between government departments that deal with water, stormwater, sewage, and land use planning will be necessary.

7.5 How Do I Make Water Reuse a Vital Part of My Adaptation Strategy?

Water reuse can be used as a response for a number of climate change issues. Figure 7.3 provides an example of potential climate change impacts under whichreclaimed water can provide an excellent adaptation strategy.

Many applications of reclaimed water are likely to become more important and valuable as climate changes. Some of the opportunities and value of water reuse in a world with climate change include the following:

- *Supplementing potable supplies.* A typical role envisioned for water reuse is as a means of supplementing potable water supplies. This may be done by providing indirect potable reuse to augment a water supply (e.g., by recharging aquifers or replenishing surface reservoirs) or by substituting reclaimed water for potable water for specific types of water use—for example, by using reuse water for turf irrigation. Climate change is likely to decrease potable supply yields in many regions, but at the same time, it is likely to increase demands (especially for outdoor irrigation).
- *In-stream flow augmentation.* This may be done to counter reduced natural instream flows that may arise from decreased precipitation. This can also alleviate elevated in-stream temperatures that are due to low summer flows and hotter ambient air temperatures.
- *Wetland creation or enhancement.* This can be done to provide more natural filtering for increased sediment and other non-pointsource loads. These types of loads are anticipated to increase because of increased storm intensities coupled with potentially longer dry periods between rainfall events, as well as watershed vegetative changes. Wetland creation or preservation using reclaimed water may also

create or enhance habitat for critical wildlife whose natural habitat may be damaged or reduced by climate change and other pressures.

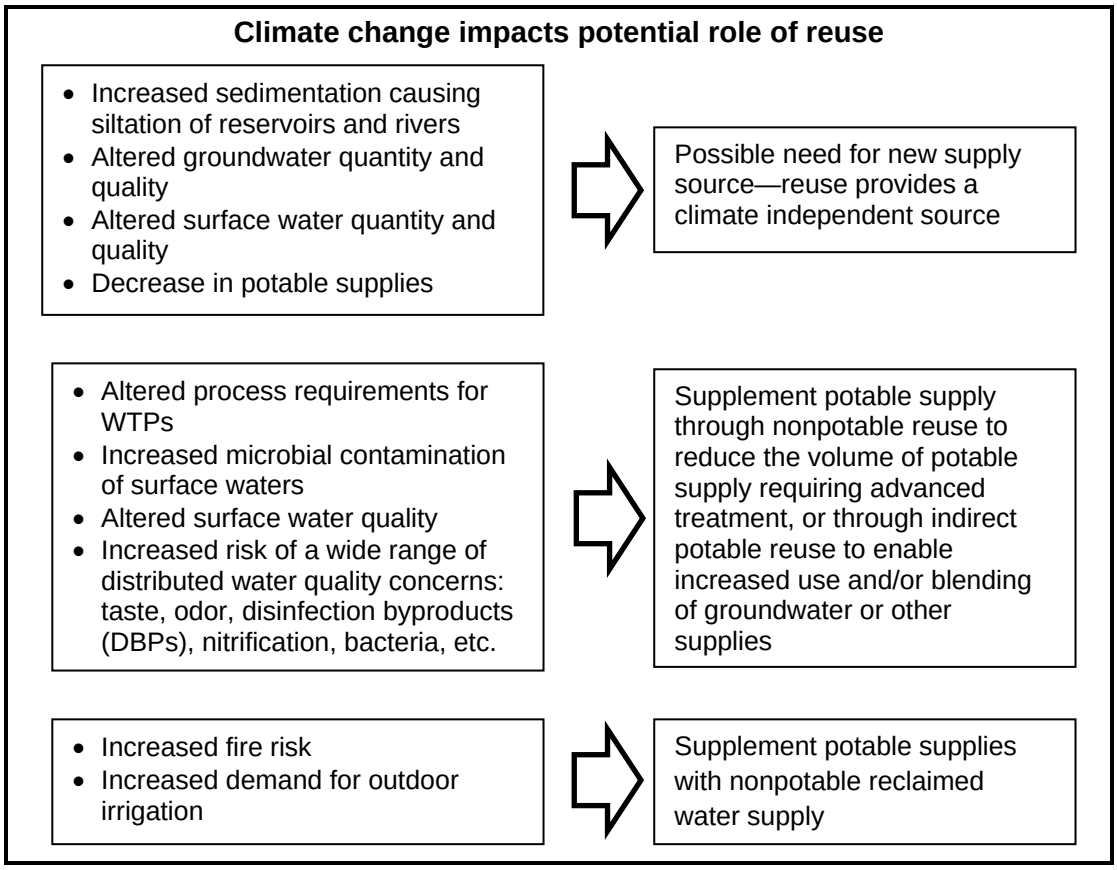


Figure 7.3. Examples of climate change impacts that can be addressed by reuse.

- *Coastal groundwater injection for saltwater intrusion barriers.* This will be especially valuable in coastal areas that rely exclusively or extensively on groundwater supplies. Projected SLR and storm surge (which may increase with higher-intensity storm events) may also result in saltwater intrusion into those critical aquifers.
- *Fire suppression and control.* With increased storm intensity, heightened drought conditions (in some regions), and other factors that may result from climate change, it is likely that there will be more and larger wildfires with climate change (e.g., drought- and pest-stressed forests and woodlands are likely to be impacted by more lightning storms). This may create the need and opportunity to use reclaimed water for fire suppression, either by increasing storage in areas where fire-fighting needs may increase or in direct fire line feeds.
- *Agricultural irrigation.*Because of higher temperatures, climate change is likely to extend growing seasons and increase irrigation demands. In some regions, it will also cause a decrease in summertime rainfall and open some northerly areas to farming activities that could use irrigation. Each of these events would create more demand for irrigation supplies, thus creating opportunities to use reclaimed water.

Figure 7.4 illustrates the broad range of applications IEUA has developed for reuse.**IEUA uses recycled water to create a flexible, adaptable program that will meet future needs given a broad range of uncertainties**

IEUA's four wastewater facilities currently produce about 60 million gallons of recycled water each day. This water is currently directed tononpotable uses including irrigation, industrial use, and recharge of the Chino groundwater basin.

In 2000, IEUA recognized that recycled water is the only source of new water for the region. In the last 10 years, IEUA and local water providers have invested in new water infrastructure, including 75 miles of recycled water pipeline within the distribution system. Plans are underway for an additional $40 million investment in new recycled water systems. Ultimately, IEUA plans to have its recycled water program self-funded through sales andMetropolitan Water District of Southern California (MWD) local project rebates.

IEUA believes that recycled water provides a clean, safe, and new source of water that will reduce reliance on expensive imported water, save money (and water!), and assist in drought-proofing the region.

Figure 7.4. IEUA and recycled water.

7.6 Will This Meet My Need to Prepare for and Adapt to Climate Change?

Preparation/adaptation is an ongoing practice for water managers.Demands change, watersheds change, and water quality and quantities change.Therefore preparation is an ongoing practice that requires you, as the resource manager, to be continually alert.But if you follow the practices outlined in this chapter,your utility will beaware of important issues and you will be able to design plans that are responsive to climate-related vulnerabilities and challenges.

Chapter 8

Coordination and Communication

This chapter concludes our discussion of the elements to include in your climate change planning with a discussion of the vital role of coordination and communication. As resources get tighter, the ability to plan alone is diminished,increasing the need for watershed planning and the coordination of multiple players. In addition, the political issues surrounding climate change make communicating and building support from your manystakeholders a special challenge. We briefly approach both subjects in this chapter. Additional information and resource links on how to develop strong communication strategies are provided in Chapter 19.

8.1 The Need for Coordination as an Adaptive Strategy

The risks of climate change can often be significantly reduced through coordination and communication. Sharing and spreading risk is how insurance companies stay in business. In addition, as your resources get tighter, the need for coordination with other resource users grows. Your utility can benefit from these strategies when preparing for climate change. Examples of additional ways to include others in your planning process and deliberations include the following:

- Create watershed-based agencies to ensure that all waters are managed effectively. See Figure 8.1 for an example of how IEUA accomplished this to great benefit.
- Establish mutual aid and other written agreements with other W/WW entities in your region to provide greater insurance. See Figure 8.2 for an example of how IEUA has made this the core of itsclimate change adaptation program.
- Communicate and coordinate with consumers, public officials, board members, interest groups, other municipal authorities, regulators, and other stakeholders.
- Create conduits and agreements with other water suppliers in your region that allow you to share supply sources. For example, if your utility has groundwater as itssole supply source and your neighbor utility has surface water as itssole supply source, consider building a supply source conduit between your two utilities. This way, both utilities have spread the risk. We encountered this adaptation in California. However, it is important to assess your utility's ability to add or switch between different water sources, as each intake from each source requires unique treatment and equipment, inputs (e.g., chemicals, electricity), and technical capacity of utility staff.
- Tap into trade associations (e.g., the WateReuse Association, American Water Works Association [AWWA], Water Environment Federation [WEF], International Water Association [IWA], and Water Services Association of Australia [WSAA]) to exchange ideas and experiences with utility peers from across the nation and around the globe. (This report is a great example!)

Working together with other southern California water users, IEUA develops a plan to maximize water resources for all

In the past, IEUA's role was simply to distribute imported waters to southern California users. Forward-thinking utility staff brought forwardthe idea that by managing the Chino Basin, they could actually increase the aquifer's ability to provide good-quality water. However, they did not have authority over the entire aquifer. In fact, no one did. By working with all the relevant players, IEUA was instrumental in the creation of the Chino Basin Water Authority and Watermaster. This new entity was empowered to make decisions affecting the entire basin. This authority was necessary before the basin could be managed effectively. Today, the Chino Basin is used to store excess imported water, stormwater, and recycled water, and the integrated application of reuse water for aquifer recharge has helped clean up the lower end of the aquifer gradient by flushing salty waters to a desalinization plant. The following graphic provides an illustration of this management strategy. Management of the basin in this effective manner is only possible through communication and coordination with all the Chino Basin players.

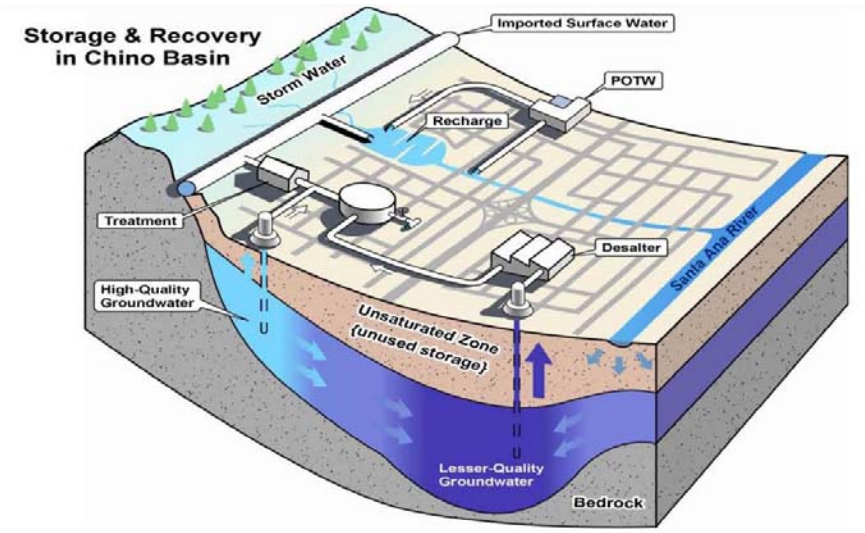


Figure 8.1. IEUA's past use of communication and coordination to create flexibility.

8.2 Communicating Resource Management Needs That Are Due to Changes in Climate without Discussing the Politics of Global Warming

If your utility is located in San Francisco, it is probably vital that you communicate with your stakeholders your plans for addressing climate change. If your utility is located in the rural South,your stakeholders probably donot want to hear about climate change. In this section, we suggest tactics for communicating issues involving changes in climate without worrying about whether or not to discuss the politics of global warming. This is done by focusing, and as needed redirecting, the discussion on good resource management. Good resource management is your overall goal as a water resource manager and should be included as a primary reason for any decision under consideration. In communicationwith a climate-change-skeptical audience, the following approaches are useful for keeping the discussion focused on resource management: no-regrets adaptations, climate variability, and prudent

planning. Remember, it is not your job to convince anyone that climate change is real;rather, it is your job to communicate the impacts of changes in climate that affect your utility.

Figure 8.2. IEUA's 2009 climate change communication strategy.

IEUA's current climate change strategy focuses on working with others

IEUA (2010) states that its current approach to climate change communication includes the following:

- Proactively working with state policymakers and legislators to target incentives in support of their energy-saving and water-saving projects
- Working with the Association of California Water Agencies (ACWA) to encourage federal and state policies to incentivize and provide financial assistance for local resource investment in conservation and water use efficiency, recycling, and renewable energy
- Working with the Santa Ana Watershed Project Authority (SAWPA) to develop integrated, regionally coordinated water resource plans and projects that can be implemented on a watershed basis and that are eligible for Department of Water Resources funding
- Using the "First Thursday" Prado Basin planning process to work with local stakeholders, such as regulators, communities, developers, and those with recreation and environmental interests, to costeffectively implement new stormwater programs that reduce runoff from hard surfaces and promote groundwater infiltration and water quality improvement
- Working with the Southern California Alliances, including the California Association of Sanitation Agencies (CASA) and the California Wastewater Climate Change Group (CWCCG), to maintain active and consistent involvement with the state's Air Resources Board as they develop and implement their scoping plan and regulations
- Promoting implementation measures that ensure that wastewater agencies receive credit for early, voluntary reductions in GHG emissions; are able to participate in the production and exchange of renewable energy credits under a proposed cap-and-trade system; and are treated fairly under proposed mandatory GHG reporting regulations and fee systems
- Working with the Metropolitan Water District of Southern California (MWD) on planning efforts such as the Integrated Regional Planning Process and preparing technical tools and decision-support models for incorporating climate change uncertainties into the water planning process

8.2.1 No-Regrets Adaptations

If an action or option makes sense for reasons that your climate-skeptical audience can accept (i.e., they make sense without climate change even being considered), then why bother talking about climate change and climate science at all? Many actions taken in response to climate change, including adding reclaimed water to your supply portfolio, can be justified on other grounds. Even if you discovered this need through a climate change analysis, and the primary reason for the decision is potential or probable changes in climate, when a benefit-cost analysis or other decision tool indicates that this is a good decision regardless of changes in climate, *resist the need to list changes in climate as the primary driving force if your audience has a large segment that is resistant to the climate change issue!* Put another way, if you have a large audience segment that is sensitive to the climate issue, then make it a point to find and present other rationales for the decision.

Reclaimed water, water use efficiency, green infrastructure, integrated water resources management, and many other adaptive strategies serve a number of economic, social, and

environmental objectives. A triple bottom-line (TBL) analysis that looks at the financial, social, and environmental benefits and costs of these programs can illustrate how regardless of climate change they still result in net benefits to the utility and the community. For example, the El Paso Water Utility recently performed a TBL analysis of their reuse and desalination programs and found that even without consideration of climate change,the programs saved them millions of dollars, reduced social impacts by millions, and had a significant positive environmental impact (Stratus Consulting, 2011).

8.2.2 Climate Variability

One thing we all know about the weather is that it changes. Rather than arguingthe cause of changes in climate, keep the discussion focused on climate variability and your utility's vulnerability to those changes. It doesnot take a climate scientist to point out the last time your utility weathered a prolonged drought, implemented water use restrictions, experienced an intense precipitation event that led to combined sewer overflows, or encountered infrastructure damage from coastal storms. These impacts are real and they affect utilities all the time, and they will happen again regardless of climate change. Theymay well be exacerbated by climate change in the future, but preparing your utility to more effectively handle the normal variability of climate is often enough to justify the proposed utility action. For example, the recent prolonged droughts in Texas may be enough to convince Texans of the need for droughtproof water supplies such as reclaimed water.

If recent climate variability is not enough to justify the decision, it may be prudent to remind your audience that climate variability has been going on for centuries (and longer!), back to what is referred to as the paleoclimate. Scientists have developed methods, such as tree ring and lake sediment analysis, to look into the past for clues about the full extent of climate variability. In almost every case, evidence indicates that extreme events hundreds of years ago, such as deep and prolonged droughts, fell far outside the range of climate variability in the observational record. In fact, records indicate that the 20th century was one of the most benign climate periods ever.

8.2.3 Prudent Planning

Finally, if all of these communication strategies fail, appeal to the conservative principles of water resources management:prudent planning requires water managers to consider potential threats to the utility and to the resource, no matter how unlikely it may seem that these threats will materialize. Water utilities routinely examine the vulnerability of their systems to massive supply disruptions, infrastructure failure, potential regulatory requirements, technological changes, and even terrorist attacks. For example, as we saw in the IEUA example, IEUA, and in fact most of southern California, is extremely sensitive to supply disruption. If IEUA had an audience that did not believe in climate change, they could discuss the need for planning for massive supply disruptions that are due to earthquakes or terrorist attacks.

Given the duty of water utilities to provide reliable, high-quality, low-cost water and/or wastewater treatment, it may be irresponsible to assume that the climate will never change. And it is prudent to investigate and plan for such potential changes, even if the changes and associated impacts never occur. Luckily for water managers, belief in climate change is not a precondition for smart management of water resources. If the term "climate change" is a consistent sticking point, consider switching and using "climate variability" instead.

8.3 What Comes Next?

Planning is an iterative process.In fact, most plans are made to be changed and updated as new information is gathered. It is particularly important to develop adaptive plans for climate change.Our understanding of how the climate is changing increases every year, providing better, more accurate forecasts. In addition, knowledge of how climate change is impacting your utility increases every year. This means that every time you go through the planning process you will have a better idea of how climate will affect your utility, the changes that need to be made to prepare for the impacts, and the role of reuse.

As you plan, we suggest you keep the following question in mind, "How will potential or probable climate changes impact my choice or ranking of options for this decision?"

We also suggest you consistently monitor your assumptions about climate change. For example, if you based your decision to put off construction of a new reclaimed water program based onthe current assessmentthatclimate change impacts on groundwater will be small, then make sure to periodically check to ensure that this projection has not changed!

In Chapters 9–11 we provide examples of how this framework for including climate change in utility planning can be applied to our case study utilities. Part III, the remaining chapters, provides an in-depth technical look at some of the issues involved in planning for climate change.

Part II

Applying the Climate Change Framework to the Utility Case Studies

Part II of this report applies the framework and tools developed and discussed in Part I to our three case study utilities. (As a reminder, this framework is presented in Figure II.1.) This is done to provide specific examples of how the framework can be applied. A summary of the information gained from each utility studied [the Miami–Dade Water and Sewer Department (MDWASD), the City of Phoenix Water Services Department (PWSD), and the Inland Empire Utilities Agency (IEUA)] is presented in Chapters 9, 10 and 11, respectively. Each of these chapters is laid out according to the planning framework,presenting the relevant information for each element for the specific utility. We conclude each case study presentation with a summary of the lessons learned through our study of that utility.

Appendices A, B, and C provide detailed, in-depth presentations oneach of the utilities studied. The detailed case studies include additional background information and detailed descriptions of water supplies, regulatory issues, etc. In addition, specific insights derived from these utilities are provided in figures in other portions of this report as useful real-world illustrations.

Element #1: Temperature and precipitation

Identify the most likely changes in precipitation and temperature for your utility location.

Element #2: Impacts and implications

Identify the direct impacts/implications for your utility of the identified changes in temperature and precipitation.

Element #3: Risks and vulnerabilities

Assess/identify the risks and vulnerabilities associated with the identified direct impacts of climate change.

Element #4: Adaptation/preparation

Prepare for highly likely and high-consequence risks and vulnerabilities by identifying adaptation strategies—including reuse.

Element #5: Coordination and communication

Identify other important players andestablish agreements for sharing risks and maximizing flexibility.

Figure II.1. Elements of a climate change planning framework for utilities.

Chapter 9

Miami-Dade Water and Sewer Department

The Miami-Dade Water and Sewer Department (MDWASD) was selected for a case study because it represents much of what may happenbecause of climate change in Florida and the southeastern portion of the United States in general—particularly in coastal areas threatened by hurricanes, droughts, sea level rise (SLR), and elevated temperatures. Appendix A provides a more detailed, in-depth description of the information gathered during our case study of MDWASD.

9.1 General Overview of the Utility

MDWASD is a W/WW utility system located in southeast Florida. The primary responsibilities of this retail and wholesale provider include water treatment, transmission, and distribution, as well as sewer collection, treatment, and disposal. On average, MDWASD serves a population of 2.2 million. It is ranked as one of the top 10 largest W/WW utilities in the United States by population served, number of accounts, and amount of water sold, and is the largest water utility in the Southeast. See the map in Figure 9.1.

MDWASD's water system services approximately 418,000 retail customers and 14 municipal wholesale customers located within Miami-Dade County and has a permitted capacity of 452 mgd. The main raw water source is the surficial Biscayne aquifer, a nonartesian (or near-surface) aquifer that underlies an area of about 3200 square miles in Miami-Dade, Broward, and Palm Beach counties. The Biscayne aquifer has been federally designated as a sole source aquifer under the Safe Drinking Water Act (SDWA) because it is considered to be the only viable water supply source for the overlying region.

MDWASD has been using reclaimed water as process water in several wastewater treatment processes, replacing and conserving potable water. MDWASD also reuses 13 mgd of treated wastewater for on-site processes, for landscape irrigation at two of their wastewater treatment plants (WWTPs), and for public access irrigation at Florida International University's Biscayne Bay Campus. MDWASD has committed to reclaim approximately 170 mgd of wastewater over the next 20 years through a number of projects, including aquifer recharge, irrigation, and coastal wetlands rehydration.

9.2 Current Management Challenges Without Climate Change Considerations

Key regulatory factors impacting water supply and wastewater management in the Miami region, regardless of climate change, include the impacts of the Comprehensive Everglades Restoration Plan (CERP), the Regional Water Availability (RWA) Rule, and the Florida Ocean Outfall legislation. The key regulatory and institutional factor impacting water reuse is the State of Florida's formal objective to encourage and promote reuse. For more details on each regulation and piece of legislation and how it will impact MDWASD, please see the complete case study presented in Appendix A.

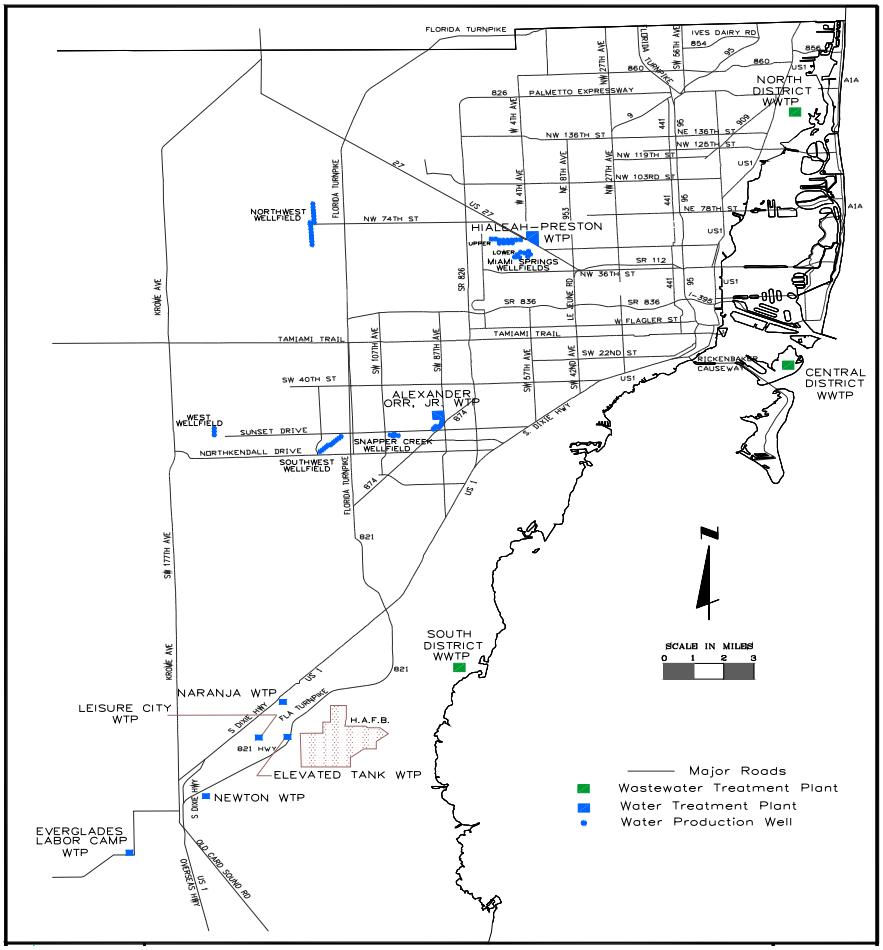


Figure 9.1.MDWASD system.
Source: MDWASD Water Production Division.

MDWASD's main potable water supply source, the Biscayne aquifer, is one of the most productive freshwater aquifers in the world because ofits high porosity and transmissivity. The region's highly seasonal rainfall pattern and limited opportunitiesfor surface water storage because of the flat topography create a significant challenge for balancing year-round water supply and demand. Specifically, if the wet season ends with high groundwater levels (to maximize storage for the dry season), significant risks of flooding can arise if late-season storms develop.

Water quality issues are primarily due to high tannins and other organics present in water derived from the Everglades and to a potential future statewide ban on phosphorus.

The most critical climate-related issues currently faced by MDWASD include the infrastructure and operational practices needed to address stormwater and flood management, and sea level rise (SLR). Although storms and floods occur periodically, their potential impacts are severe and thus seen by many as more critical than water quantity or water quality. During periods of excessive rainfall or in anticipation of major rainstorms or hurricane landfall, water levels in the canals and the water table in the Biscayne aquifer are lowered to increase stormwater storage capacity. The key issue in stormwater and flood

management is how to manage the Biscayne aquifer water levels. It is important to strike a balance between the need to keep aquifer capacity available for stormwater management and the need to store freshwater for possiblehigher demands in drier seasons. In addition, the requirements of the CERP program need to be met with respect to groundwater levels.

9.3 Element 1: What Changes in Temperature and Precipitation Is MDWASD Most Likely to Face?

To illustrate the usefulness of easily accessible information, we look at the most current information available from the United States Global Change Research Program (USGCRP). The map in Figure 9.2 illustrates potential changes in temperatures and Figure 9.3 provides a summary of the other "most likely" climate change impacts for this region.

9.4 Element 2: What Are the Implications for MDWASD of the Identified "Most Likely" Potential Climate Change Impacts

To identify the likely utility implications of the most likely potential climate change impacts, we use the flow diagrams found in Part III, Chapter 15. For this example, we narrow the climate change impacts of most concern for MDWASD to the impact of sea level rise (SLR) for wastewater management and the impacts of more an intense rainfall event for water supply, Figures 9.4 and 9.5, respectively.

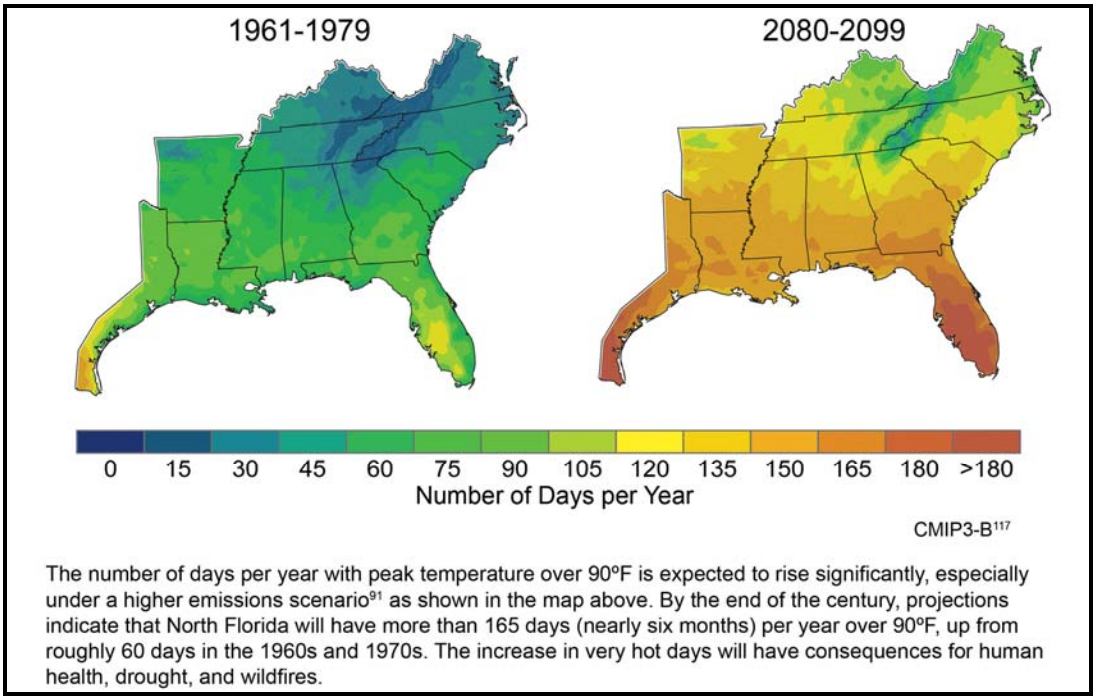


Figure 9.2.Past and projected number of days per year with peak temperature above 90 °F for the U.S. southeastern region.

Source: USGCRP, 2011a.

- Continued warming is projected, with the greatest temperature increases in summer. The number of very hot days is projected to rise at a faster rate than average temperatures. Average annual temperatures are projected to rise 4.5 °F under a lower-emissions scenario and 9 °F under a higher-emissions scenario, with a 10.5 °F increase in summer and a much higher heat index.
- Sea-level rise is projected to accelerate, increasing coastal inundation and shoreline retreat.
- There will continue to be an increase in heavy downpours.
- The intensity of hurricanes is likely to increase, with higher wind speeds, greater rainfall intensity, and greater storm surge height and strength.

Figure 9.3. Summary of USGCRP (2009) findings of potential climate change impacts for the southeastern United States.

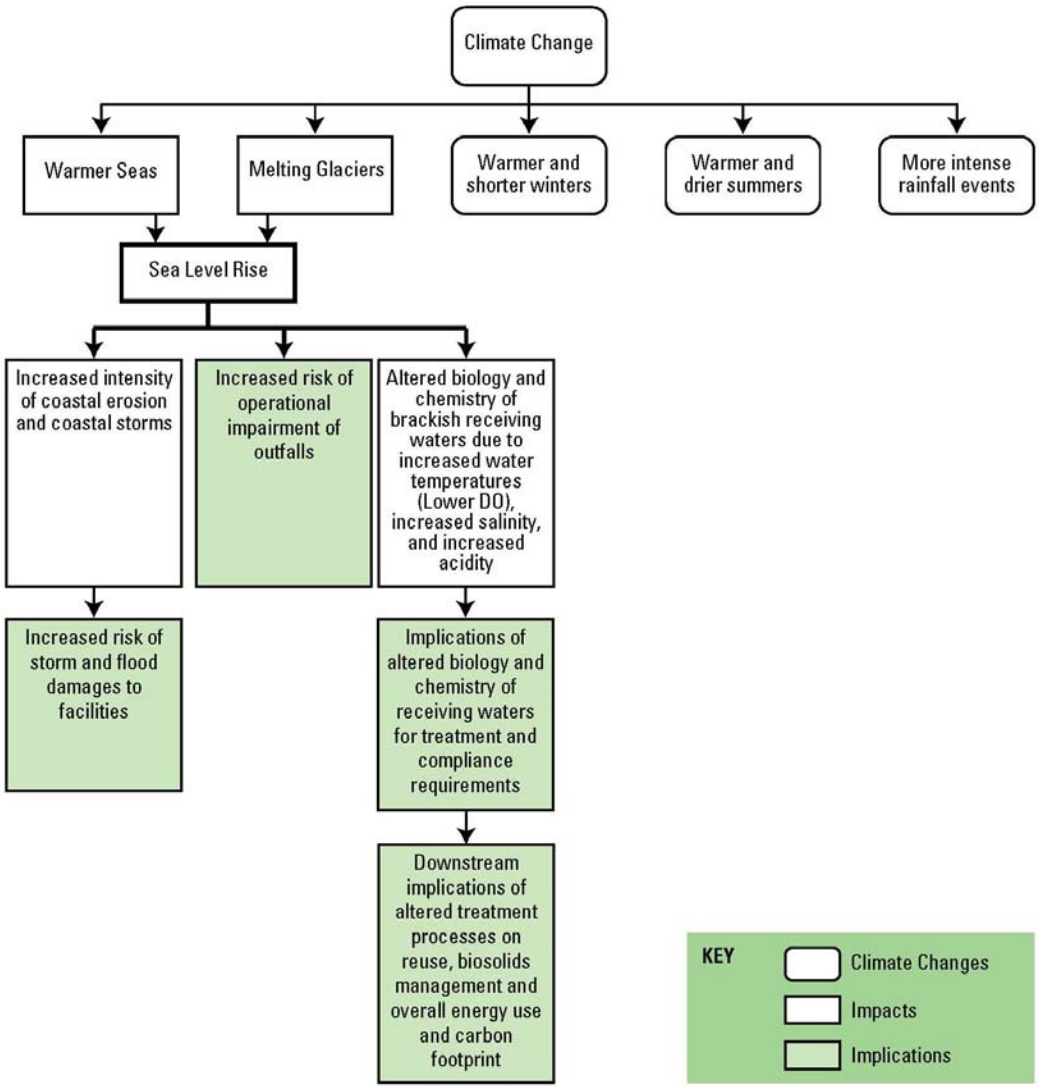


Figure 9.4.Impacts and implications of SLR for wastewater utilities.
Source: WERF, 2010.

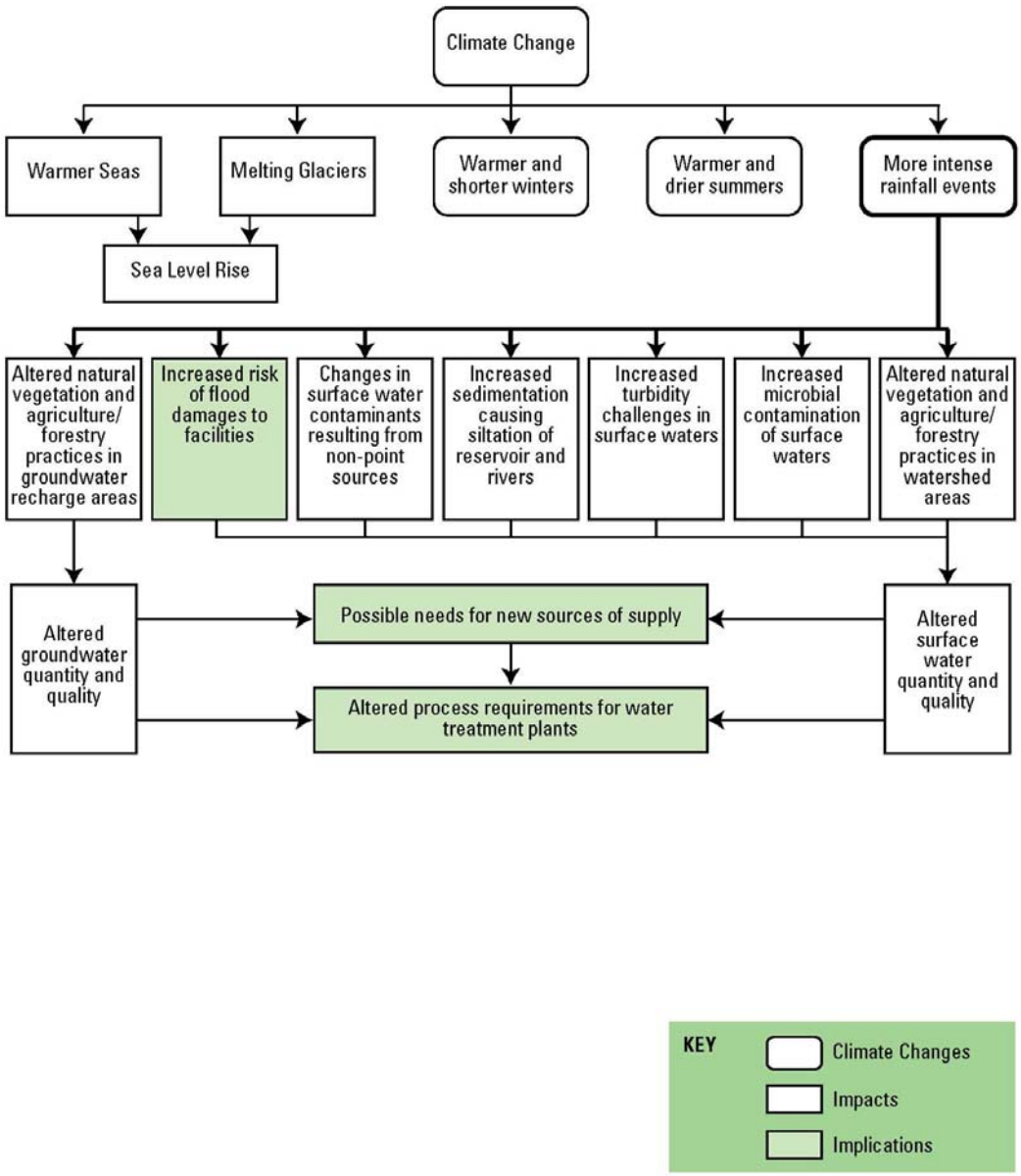


Figure 9.5. Impacts and implications of more intense rainfall events for water supply.
Source: Cromwell et al., 2008.

9.5 Element 3: What Risks and Vulnerabilities Associated with Climate Change Are Important for MDWASD?

In this step MDWASD needs to include the concerns raised in the flow charts in all of their planning discussions. Note that the majority of the identified concerns relate to infrastructure. It is interesting to note that in our discussions with MDWASD their expressed concerns about climate change were primarily related to SLR. One way MDWASD could choose to use this information is to send a briefing to their managers sharing the information identified during their identification of climate changes and climate change implications and asking managers to consider the information gathered whenever appropriate in their decisionmaking.

MDWASD could also choose to address the issues more directly through a tipping point or risk assessment analysis. If MDWASD chose to use the tipping point approach for identifying where climate change impacts represent significant areas of concern for current management issues, they would most likely identify the following areas of concern:

- *Saltwater intrusion:* Saltwater intrusion associated with SLR and increased coastal storm surge will result in increased total dissolved solids (TDS) concentrations in water supply sources. As a result, it may be necessary to install additional water treatment processes to provide high-quality drinking water, move regional water fields inland, use supply from a lower aquifer of lesser quality, or expand the stormwater management canal system.
- *State regulation:*The ban on ocean outfalls, coupled with the mandate that at least 60% of the water formerly discharged be further treated and reused, will require changes to MDWASD's wastewater collection system and treatment processes to make reclaimed water suitable for reuse.

Our discussions with MDWASD indicated that their climate change planning was focused on the issues presented by SLR. Serious consideration had not yet been given to the impact of climate change on aquifer management. MDWASD also needs to consider the following tipping point in their planning discussions:

- *Seasonality:* Seasonality will have an impact on stormwater and flood management. It may require an increased need for flexibility, balancing the need to maintain aquifer capacity for stormwater storage during wetter wet periods withstoring fresh water for possibly higher demands during potentially drier seasons.

9.6 Element 4: What Adaptation/Preparation Options, Including Reuse, Should MDWASD Consider?

A recurring theme in offsetting SLR and drought caused by climate change is the need to provide and maintain as much freshwater in the hydrologic system as possible within the constraints of stormwater management. The alternatives include several potential roles for water reuse and break down into the following four categories:

1. Protection of existing water sources
   - Hydrodynamic barriers can help protect against saltwater intrusion in vulnerable wells.
   - The Biscayne aquifer can be recharged through surface recharge or direct injection of reclaimed water. The added water would provide beneficial use but may contribute to flooding during the rainy season as sea level rises. These options could lead to very high treatment costs.
   - Recharge of the lower, and partly saline, Lower Floridian aquifer would be a potential high-value beneficial water reuse application with no anticipated adverse impacts from climate change. However, it requires higher-cost treatment, the concept has not been implemented to date, and there are potential environmental concerns.

- Recharge of the Everglades with highly treated wastewater may be an attractive long-term solution to help meet CERP goals.

2. Reclamation and reuse of treated wastewater for nonpotable supply
   - Irrigation: Reclaimed water could be used in many communities for agriculture, golf courses, residential lawns, municipal medians, and other green areas, instead of water from irrigation wells. This would reduce the competition for groundwater supplies.
   - Industrial use of reclaimed wastewater: MDWASD is considering supplying 70 to 90 mgd of treated wastewater to the Florida Power and Light Company's (FPL's) Turkey Point nuclear power plant.
3. Development of alternative water sources for potable supply augmentation
   - To date, there have not been any discussions ofdirectly augmenting the potable supply with highlytreated reclaimed water (i.e., direct potable reuse). However, a number of the recharge options discussed could increase the reliability of potable water sources (e.g., indirect potable reuse).
4. Stormwater management
   - Stormwater could be treated and delivered to the Everglades Water Conservation Areas (WCAs), where it could be stored and delivered as necessary to the southern Everglades.

9.7 Element 5: With Whom Does MDWASD Need to Communicate and Coordinate?

Planning for the effects of climate change requires a regional approach because the activities of others can impact MDWASD and vice versa. For instance, pumping and water use in one county can affect the quantity and quality of water for downgradient users and can affect how these users plan for flood control. An integrated regional program can also offer opportunities for the development of advanced water treatment technologies at the same time that it reduces the incremental impacts to water utility ratepayers through sharing of costs and risks. By pooling resources to undertake major infrastructure projects, utilities can take advantage of economies of scale.

Interregional water planning would also help utilities prepare for interoperability between districts in the event of extended but geographically disparate drought conditions brought on by climate change. Miami-Dade has already taken steps to engage surrounding counties by entering into a regional coalition with Broward and Palm Beach counties.

9.8 Lessons Learned from the MDWASD Case Study

MDWASD is already on a path to integrating reuse into itswater management program. Although the drivers for this have mostly been regulatory in nature (CERP, the RWA Rule, and Florida Ocean Outfall Legislation), the resulting projects will also help the utility prepare for the effects of climate change (making reuse a no-regrets climate change adaptation). However, some important complicating factors could influence the extent to which water reuse is used for planning at MDWASD. Four of these factors are as follows:

- Use of reclaimed water for aquifer replenishment may not be a viable strategy during wet periods, because there is a need to keep aquifer storage capacity available to store rainy-season runoff. This creates a seasonality dimension to when water reuse can be applied for aquifer replenishment and creates an impediment to reuse options.
- Management of the Biscayne aquifer level is critical for meeting regulatory requirements for sustaining and restoring water levels in the Everglades. If MDWASD uses reclaimed water to create a seawater intrusion barrier, this willoccur on the eastern (coastal) portion of the aquifer and willnot be recognized by the regulator [the South Florida Water Management District (SFWMD)] as an Everglades-relevant offset. Thus, the utility has little incentive to apply reclaimed water to seawater intrusion barriers, because this application of reuse would receive no regulatory credit toward the utility's Everglades-related obligations.
- As sea level rises and floods areas that are currently habitable, irrigation needs in these areas will be reduced. The consequence is a potential reduced demand for recycled water in coastal areas. In addition, increased total dissolved solids (TDS) from inflow and infiltration into sewer mains and sewer line leakage that is due to saltwater intrusion and storm surges, coupled with SLR, could drive up treatment costs for reuse, because additional chloride and TDS-removal capability will be needed.
- The utility (and the county in general) has focused almost exclusively on SLR as the climate change impact of consequence to the region. As a result, the implications of other important climate change impacts, such as potential changes in the annual and seasonal precipitation patterns, have not been studied as thoroughly. The demand for reuse water for irrigation could increase because of higher evapotranspiration (temperature effects) and possibly drier conditions (lower precipitation) in the dry season. However, as the SFWMD rules do not currently provide water credits for displacement of irrigation wells, the utility has less incentive to develop reclaimed water for this purpose.

Utilities in the Southeast that consider water reuse when planning for the effects of climate change must ensure that these plans are incorporated into their existing water management structure. Utilities such as MDWASD must balance the need to take proactive measures with regard to climate change with the need not to move too far, too fast. By emphasizing a "no regrets" and "low regrets" strategy, MDWASD can be responsive both to climate change adaptation needs and to the need to increase overall resiliency and sustainability. Increased governmental incentives for implementing reuse projects would help offset the higher costs needed for treatment and help utilities achieve a more sustainable portfolio.

Chapter 10

City of Phoenix Water Services Department

The following is asummary of our case study for the City of Phoenix Water Services Department (PWSD) using the framework developed in Part I. A complete, in-depth look at the information gathered during the case study is presented in Appendix B. This case study was selected because it provides a study for a utility located in a region with the largest projected impacts from climate change.

10.1 General Overview of the Utility

PWSD provides water to more than 1.5 million residents within the incorporated area of Phoenix and a portion of the Town of Paradise Valley. The city's potable water system includes about 30 active groundwater wells and six surface WTPs that draw water from the Colorado River via the Central Arizona Project (CAP) and from the Salt and Verde rivers via the Salt River Project (SRP). The treatment plants and active well network have a total production capacity of close to 700 mgd. In addition to water supply activities, the city treats more than 250 million gallons of wastewater each day, servicing more than 2.5 million residents (including facilities co-owned with the cities of Mesa, Glendale, Tempe, and Scottsdale). Phoenix's wastewater system includes two wastewater plants, a reclaimed water plant, and almost 5000 miles of sewer mains.

In normal supply years, more than 90% of the city's demand is met using surface water provided through SRP and CAP. Though the city has never incurred a surface water shortage, future severe drought conditions in the source watersheds could result in delivery reductions from these projects. The city's well-diversified water resources portfolio, substantial storage in SRP and Colorado River reservoirs, and declining per capita water use have provided a buffer that has allowed the city to make full deliveries to customers over the past 15 years of dry conditions in the source watersheds.

Approximately 40% of water delivered to all Phoenix customers (residential and nonresidential) ends up at one of the city's three WWTPs, where it is treated for other uses. In total, the city treats about 125,000 acre-feet of wastewater from its service area each year. More than 90% of that treated wastewater is reclaimed and used to meet nonpotable water demands in the region.

The city's water reuse program for turf facilities was initiated in 2000 with the construction of the 8-mgd Cave Creek Water Reclamation Plant (CCWRP), which delivers reclaimed water to turf facilities in northeast Phoenix. Approximately 2000 acre-feet of water per year (AFY) has been generated for delivery to turf facilities, and the plant can produce up to 8000 AFY at its current capacity. A groundwater recharge facility at the plant provides system flexibility to address seasonal variations in outdoor irrigation demand. In 2009, this plant was temporarily closed to reduce operational costs, and the wastewater has been sent to the 91st Avenue WWTP. The city expects to restart the plant in 2012.

In addition, Phoenix is a member of the Sub-Regional Operating Group (SROG), a cooperative of Valley cities that own and operate the 91st Avenue WWTP. Treated reclaimed water from this plant is delivered to the Buckeye Irrigation Company (BIC) via the Salt and Gila rivers. This reclaimed water also serves as a valuable source of cooling water for Arizona Public Service's Palo Verde Nuclear Generating Station. Treated wastewater from the plant is also delivered to the constructed Tres Rios Wetlands, which provide advanced treatment and also creates valuable wildlife habitat and natural aesthetics to the region.

Phoenix also delivers 30,000 AFY of reclaimed water from the 23rd Avenue WWTP to the Roosevelt Irrigation District (RID), where it is used for irrigation. In exchange for this water, the RID provides a like amount of groundwater to the SRP canal system. SRP then delivers 20,000 AFY of this canal water to Phoenix WTPs and 10,000 AFY to the Salt River Pima-Maricopa Indian Community (SRPMIC). Phoenix may use SRPMIC's unused water in any year.

10.2 Current Management Challenges without Climate Change Considerations

Phoenix's water supplies exceed current demand primarily because ofthe city's diverse water supply portfolio, as well as other factors including decreased per capita water use. The State of Arizona has granted a Designation of Assured Water Supply to the City of Phoenix, affirming that at least 100 years' worth of water is available to serve existing customers. The city estimates that without adding any additional sources of supply and assuming normal supply (nondrought) conditions, it will have enough water to meet the demands of existing customers and all expected growth that will occur in the 50-year planning period. Also, under scenarios that assume severe shortage conditions in source watersheds, the city would not be faced with a supply deficit before 2020.

Despite the relative abundance of Phoenix's water supply in the short term, the city has begun to plan for a number of uncertainties in terms of more long-term supply options. These uncertainties include the timing and length of reduced inflows from SRP or CAP, growth and development in the upper Colorado River Basin, institutional decisions (e.g., Colorado River negotiations), climate change impacts, environmental mandates, water quality impacts, long-term groundwater availability, and the ability to fund acquisitions and infrastructure.

10.3 Element 1: What Changes in Temperature and Precipitation Is PWSD Most Likely to Face?

PWSD has worked extensively with researchers from the University of Arizona and elsewhere, under the National Oceanic and Atmospheric Administration's (NOAA's) Regional Integrated Sciences and Assessments program, the Climate Assessment for the Southwest (CLIMAS). This partnership has provided a wealth of information on the potential impacts of climate change on Phoenix using a range of different GCMs and GHG emissions scenarios, downscaling the geographic scale for the Salt River Project (SRP) watershed, and then placing the climate outputs in a detailed hydrologic model of the SRP reservoir system.

Some GCMs produced results that indicate a wetter future (perhaps because some of these GCMs may predict stronger monsoonal effects,whichcould increase summertime precipitation in the region); other GCM-generated outputs point to a drier future (perhaps

because they predict smaller monsoonal effects that are outweighed by a broader projected trend toward drying in the region). PWSD staff observed that precipitation projections under the GCM-based exercise presented a range that was too large and uncertain to be useful fortheir planning purposes. Consequently, the climate change information developed in partnership with CLIMAS has been used to inform PWSD managers, but not used as inputs into their planning and management models. Instead, PWSD has found retrospective paleoclimate information to be more useful, as it indicates the severity and duration of droughts experienced in the region over the course of several past centuries (thus setting up a possible worst-case scenario drought that can be used to help guide planning efforts).

The IPCC notes that the southwestern United States faces some of the most dramatic projected impacts from climate change in the country. The Southwest's relatively arid continental climate leads to hightemperatures, inconsistent seasonal precipitation, and snowmelt-dominated watersheds. According to the USGCRP, the average temperature of the Southwest has already increased about 1.5 °F over the 1960–1979 baseline. Furthermore, temperatures in the region are projected to rise approximately 4 °F to 10 °F by the end of the century, significantly more than the global average (Karl et al., 2009). A recent study by Seager et al. (2007) found a broad consensus among projections from 19 GCMs used in the Fourth Assessment Report of IPCC that the Southwest will dry significantly in the 21st century.

Droughts are perhaps the most important facet of the climate change projections for the Southwest. In conjunction with warmer temperatures, earlier snowmelt, and projections of decreased precipitation, the possibility of more frequent or more severe droughts is a critical issue for the Southwest. Despite many uncertainties, most projections point to an increasing probability of drought for the region and a substantially drier future (e.g., Meehl et al., 2007b; Seager et al., 2007; Karl et al., 2009).

10.4 Element 2: What Are the Implications forPWSD of the Identified "Most Likely" Potential Climate Change Impacts?

Figure 10.1 illustrates the implications of warmer and drier summers for the wastewater segment of PWSD, and Figure 10.2 illustrates the implications for water supply.

A summary of these findings will be useful for PWSD as a planning tool that can be included in all management decisions.

10.5 Element 3: What Risks and Vulnerabilities Associated with Climate Change Are Important for PWSD?

Climate change may impact Phoenix in a number of important ways. Higher temperatures and increasing storm intensities and flooding events could significantly affect water quality. For example, a 2005 boil water order in Phoenix stemmed from a severe rainstorm following a long drought period in part of the upstream watersheds that feeds SRP water to the Val Vista WTP. This in turn led to unusually high turbidity levels in PWSD source waters, exceeding the treatment capacity of the city's operable filtration plants. In addition, more frequent and more severe droughts may have important effects on water supply and drought management operations and capital investments. Increasing frequency and severity of flooding events could affect water supply and treatment infrastructure as well.

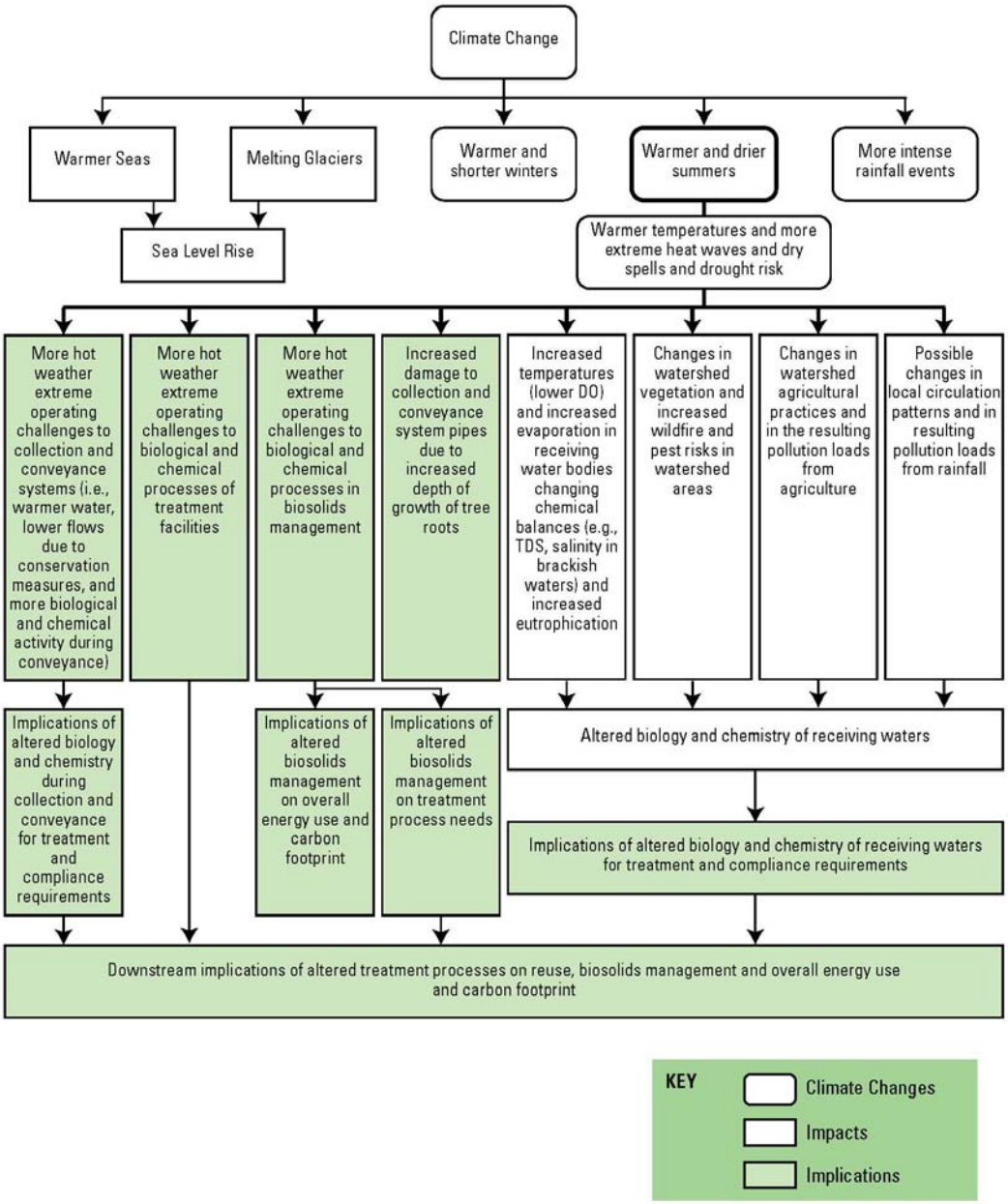


Figure 10.1.Impacts and implications of warmer and drier summers for wastewater agencies.
Source: WERF, 2010.

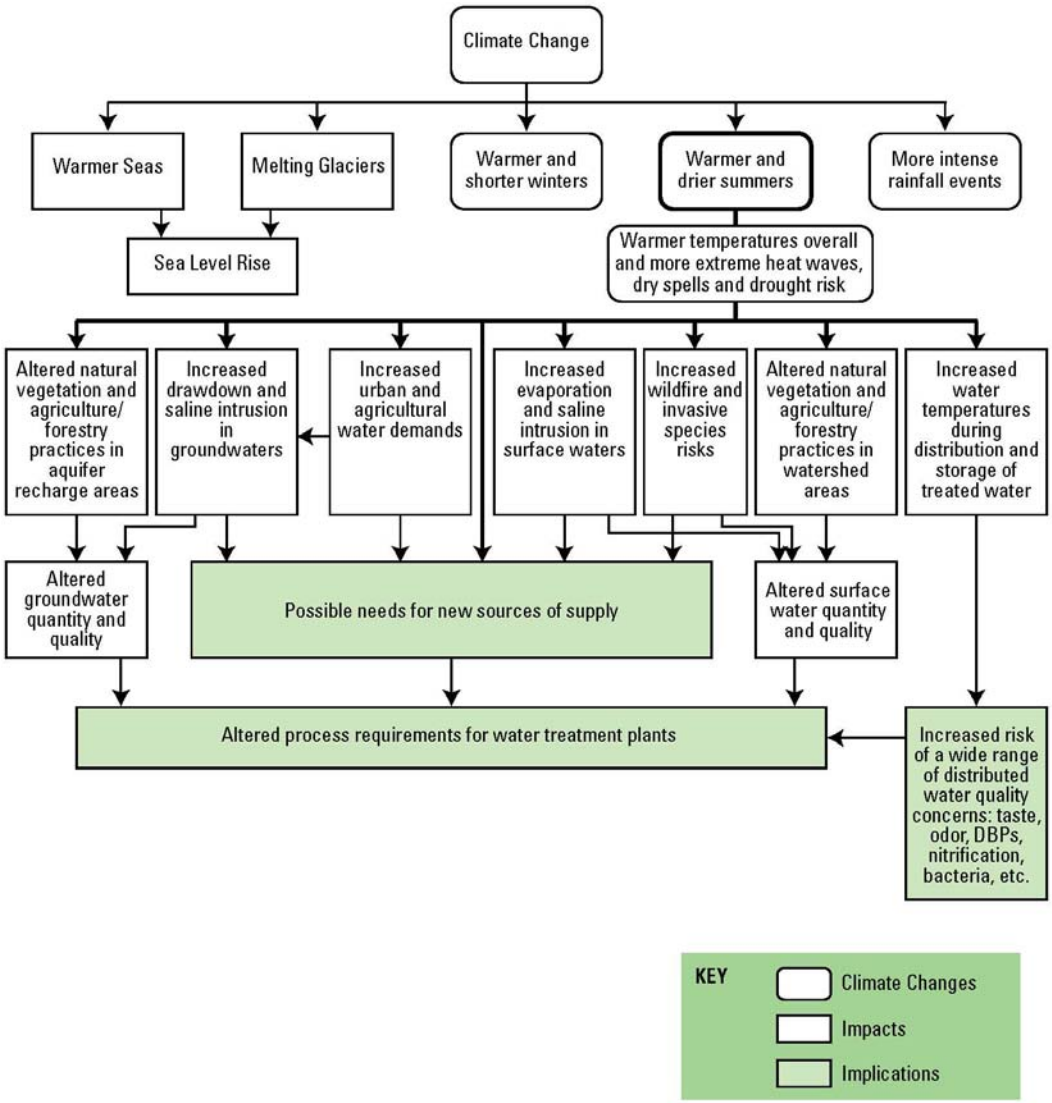


Figure 10.2. Impacts and implications of warmer and drier summers for water supply.
Source: Cromwell et al., 2008.

To account for these uncertainties, Phoenix has developed a comprehensive planning framework that includes the development of various planning scenarios. The planning scenarios account for differences and uncertainties associated with (1) the availability of supplies (based on climate and other factors), (2) future demand (including differences in growth and development patterns), and (3) conservation levels. For the development of PWSD's 2005 Water Resources Plan, 144 scenarios were developed based on these different factors.

10.6 Element 4: What Adaptation/Preparation Options, Including Reuse, Should PWSD Consider?

PWSD is already actively using water reuse as part of its current water supply portfolio, with 90% of the wastewater generated at its wastewater treatment facilities going into reuse. However, with climate change and other uncertain future conditions that may impact supply and demand, PWSD is considering ways to increase the flexibility and value of its reclaimed water.

Currently, all water reuse is directed to nonpotable applications. PWSD recognizes that in the future—because of climate change or other possible conditions—there will be considerable value in (1) providing a way to store excess reclaimed water, especially when excess water may be available because of the seasonal nature of irrigation demands, thus making it available in especially dry seasons, and (2) working toward regulatory and other acceptance for using reclaimed water for possible potable reuse (either direct or indirect potable reuse). By pursuing either or both of these options, PWSD is looking to gain important flexibility in itspotential use of reclaimed water in the future.

Another adaptation being explored by PWSD is to obtain approval for an aquifer recharge program (which would make it possible to extract groundwater downgradient if and when needed to supplement their existing surface-dominated supplies) or an ASR program (which would make it possible to store excess water, including reuse water, for use when needed, for whatever purposes are most valuable). PWSD is working proactively with State of Arizona regulators to update existing regulatory barriers to these approaches, with the objective of easing institutional hurdles and thus improving their chances of moving forward with these options in the future.

10.7 Element 5: With Whom Does PWSD Need to Coordinate and Communicate?

PWSD planners have been thinking proactively about how to increase the flexibility and value of their water reuse program. Their efforts to explore these options, and to actively engage with state officials to clear a path through existing regulatory hurdles, reflect good foresight and initiative.

10.8 Lessons Learned from the PWSD Case Study

At least three important lessons can be drawn from the efforts and experiences of PWSD with regard to planning in the context of climate change and water reuse.

First, the Phoenix experience provides an observation about how a top-down approach—even when using the most sophisticated, state-of-the-science models and science—may not provide actionable information to water planners.

Second, PWSD planners have been thinking proactively about how to increase the flexibility and value of their water reuse program. Their efforts to explore these options, and to actively engage with state officials to clear a path through existing regulatory hurdles, reflects good foresight and initiative. These proactive efforts reflect a no-regrets adaptation strategy because they add flexibility and value regardless of whether or how climate changes. An ASR

or comparable water reuse strategy that enables storage and/or potable reuse also represents a no-regrets options, as it will probably provide even greater value under climate change.

Finally, the PWSD planning approach provides a useful articulation of how to turn the general concept of "adaptive management" into implementation in a practical planning context. For example, PWSD has a clear understanding of the timeline for response, which in turn indicates when to switch from an advance planning and observation mode to a more active mode of implementing adaptation strategies. That is, PWSD has identified the switch point for when watching and planning needs to turn into action, based on their recognition of the amount of time it takes to implement a given suitable response. This useful perspective helped frame the general guidance for adaptation provided in Part I of this document.

Chapter 11

The Inland Empire Utilities Agency

The following is the summary of our case study ofIEUA using the framework developed in Part I. A complete, in-depth look at the information gathered during the case study is presented in Appendix C. This case study was selected because it provides an example of an agency that has had extensive experience in planning for climate change and illustrates the role water reuse can play in developing and implementing flexible water utility plans.

11.1 General Overview of the Agency

IEUA is a wholesale regional distributor of water and recycled water and also provides regional wastewater treatment services for a 242-square mile area of western San Bernardino County that overlies the Chino Basin (Figure 11.1; IEUA, 2010). In 2007 the IEUA service population was estimated to be approximately 800,000.

IEUA serves eight water retail agencies and works to coordinate its water resource management program with the Chino Basin Watermaster, the San Bernardino County Flood Control District, the Chino Basin Water Conservation District, and local water and sewer retail agencies. IEUA is a member of the Metropolitan Water District of Southern California (MWD).

IEUA also coordinates wastewater treatment services with seven wastewater contracting agencies. Industrial and municipal wastewater is managed through a network of regional wastewater sewer interceptors and two nonreclaimable wastewater (NRW) sewer pipeline systems; treatment at five regional treatment plants; biosolids management; and other related wastewater utility services. IEUA has a total wastewater treatment capacity of 60 mgd. The agency also owns a co-composting facility and has a managing interest in the Chino 1 and 2 desalters.

In its 2008/2009 Annual Report, IEUA's then President Richard Atwater stated, "IEUA views its business as manufacturing three products: high-quality recycled water to help drought-proof our service area, converting high-quality compost to ensure healthy solids, and renewable energy through methane gas and solar generation facilities."

The Chino groundwater basin is the largest in southern California, currently containing 5 million acre-feet (AF) of water, with an unused storage capacity of an additional 1 million AF. Water rights within the basin have been adjudicated, and the average safe yield of the basin is 140,000 AFY. During the past two decades, the IEUA service area has consistently been one of the fastest-growing regions in the nation. With a local water supply that consists primarily of an overdrawn salt-laden aquifer (the Chino Basin) and with the purchase of expensive imported waters being the only obvious way to meet the growing demand for water, IEUA has a planning challenge.

Figure 11.1. IEUA location map (shaded area, largely in southwest San Bernardino County).
Source: IEUA, 2010.

IEUA met this challenge by developing, in partnership with other key basin management players, the Groundwater Recharge Regime program. This program manages the Chino Basin aquifer in a manner that both increases supplies and improves water quality.It also limits groundwater use to the adjudicated safe-yield level and ensures that downstream users' needs are met in terms of both quality and quantity.

Figure 11.2 is an illustration of IEUA's Chino Basin Groundwater Recharge Regime program. Both the recharge and desalting wells are hydrologically placed to take advantage of the groundwater gradient. The recharge of high-quality reclaimed water upgradient provides a hydrological push to help move (as well as dilute) the lower-quality groundwater in the downgradient direction. At the same time, desalter well extractions provide the pull at the low end (IEUA, 2010).

The groundwater recharge program is designed to maximize the use of all local waters. High-quality stormwater and recycled water are used to recharge the basin;at the same time, desalting removes the concentrated salts downgradient, providing downstream users with a greater flow of high-quality water. IEUA has accomplished this, in part, by developing legal and regulatory agreements that benefit the entire region and by developing a new source of water rarely considered 20 years ago—recycled water.

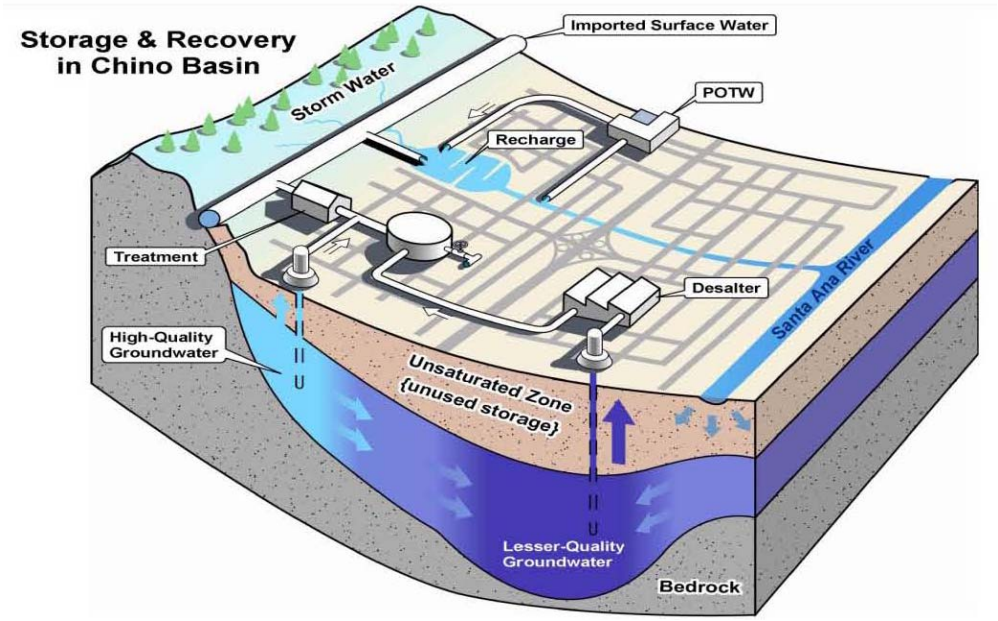


Figure 11.2.Chino Basin Groundwater Recharge Regime.
Source: IEUA, 2010.

11.2 Current Management Challenges without Climate Change

In its2010 planning document, IEUA identifies the following uncertainties that must be addresses as itdevelops a plan for the future:

- Population growth and changes in water usage
- The reliability of both local and imported water supplies
- The ability to raise funds given the current and projected economic challenges
- The ability to bring together myriad participants, and the public's perceptions of needs (IEUA, 2010)

11.3 Element 1: What Changes in Temperature and Precipitation Is IEUA Most Likely to Face?

In 2006 the California Climate Change Center and California Energy Commission stated that for the IEUA region, temperatures are very likely to increase and annual average precipitation may either increase or decrease. The commission also noted that these trends will have significant impacts by increasing demand for irrigation; generating more intense and possibly less frequent storms; diminishing the Sierra snowpack, which provides imported water supplies; and decreasing local groundwater recharge.

11.4 Element 2: What Are the Implications for IEUA of the Identified "Most Likely" Potential Climate Change?

IEUA has participated in a number of analyses of the implications of the most likely potential climate changes. The two most important of these arethe report by the Public Policy Institute of California (PPIC), part of the University of California at Davis, *Climate Warming &*

California's Water Future, and the RAND Institute report, *Preparing for an Uncertain Future Climate in the Inland Empire.* These large "top down" computer analyses are discussed in more detail in other portions of this report. In this section we review only the relevant findings.

The PPIC study looked at how the entire California water infrastructure could adapt and respond to potential changes in climate in the context of larger future populations, changes in land use, and changes in agricultural technology. Their primary conclusion for IEUA—look out for yourself, because potential climate changes (particularly changes in snowpack) are likely to result in the inability of the California conveyance system to provide the IEUA region (and the rest of southern California) with any increases in imported water supplies. This implies that maximizing the use and prudent management of locally available water resources makes goodsense as part of a climate change adaptation strategy, and this in turn means making the greatest use possible of reclaimed water.

The RAND study essentially reached the same conclusion, albeit via a different analytic path, as discussed in the next section. The ability of IEUA to adapt to RAND's assessment of climate change scenarios was critically linked to the utility's ability to successfully implement its water reuse strategies as completely and extensively as possible.

11.5 Element 3: What Risks and Vulnerabilities Associated with Climate Change Are Important for IEUA?

IEUA's participation in RAND's large "top-down" analysis examined how potential climate change affects current planning options. This decision-support analysis focused on the effectiveness of the planning scenarios developed in the IEUA 2005 Regional Urban Water Management Plan (RUWMP) in meeting projected future needs given projected regional climate changes. The IEUA RUWMP lays out three strategies for achieving this objective:

1. Increase the long-term yield of Chino Basin groundwater production through conjunctive use and hydrologic control (e.g., through groundwater recharge with reclaimed water)
2. Expand the treatment and distribution of wastewater for reuse by urban users (i.e., nonpotable reuse using purple pipe)
3. Develop regional agreements with other agencies to increase flexibility in water management, such as the 2003 dry-year-yield (DYY) program agreement with the MWD

Note that the scenarios developed in the 2005 RUWMP all include *significant* increases in the role of reused water.

The RAND study used three decision support tools (DSTs) to model uncertainty and present information about IEUA's RUWMPs and their effectiveness given a range of potential climate changes.

1. The traditional scenario analysis demonstrated that IEUA's RUWMPs would perform well if climate conditions were wetter than current conditions, even with incomplete implementation of the water recycling and replenishment goals. If the future climate were drier and warmer, IEUA would need to meet its recycling and replenishment

goals, invest in more efficiency, and possibly allow more recycledgroundwater replenishment to ensure sufficient supply to meet demand.

2. The probability-weighted scenario suggests that if one believes the underlying probabilistic information about future climate and the IEUA region's ability to meet its recycling and replenishment goals, the current IEUA RUWMP would be sufficient to ensure only a 7% chance of a shortage.
3. Finally, the policy-relevant scenario identified two critical scenarios that are the most threatening to the success of IEUA's water management plan—a dry, flashy low-recycling scenario and a wet effective-recycling scenario. Under these conditions, the IEUA RUWMP is unlikely to perform well. Additional efficiency and groundwater-management strategies improve performance for one scenario (thethe dry flashy, low-recycling scenario) but also leads to greater surpluses. The analysis suggested that if managers think that future conditions are more than 25% likely to be consistent with the dry, flashy low-recycling scenario, a policy with greater efficiency or more use of recycled water for replenishment would be prudent (RAND, 2008).

11.6 Element 4: What Adaptation/Preparation Options, Including Reuse, Should IEUA Consider?

In 2007, IEUA adopted an aggressive three-year business plan designed to implement the increased use of recycled water. The goals of the plan are to provide 50,000 AFY to meet anticipated demand by June 2012; provide 100,000 AFY of recycled water in the future; make the recycled water program self-funding through sales and MWD rebates; and keep construction costs below $250 million.

IEUA's adopted Recycled Water Feasibility Study (August 2002) indicated that by the year 2020, the projected use of recycled water would exceed 70,000 AFY, with more than 1700 customers projected to be connected to the regional recycled water distribution system. Subsequent implementation of the 2005 Recycled Water Program Implementation Plan and the 2005 IEUA Urban Water Management Plan (UWMP) showed that more than 93,000 AFY of recycled water could be delivered to more than 1900 potential customers. In addition, IEUA will recharge up to 33,000 AFY of this recycled water (blended with stormwater and imported water to meet the overproduction replenishment needs) into the Chino Groundwater Basin and facilitate direct deliveryof more than 60,000 AFY of recycled water to local customers.

IEUA's goal is to use as much recycled water for local beneficial uses as is economically practical and also to replenish the Chino Groundwater Basin. In June 2007, IEUA received a new permit for recycled water recharge. As a result, several more basins that can be utilized for recharge with recycled water were added. These basins will increase both the volume and distribution of recycled water in the Chino Basin. Ultimately, maximized use of recycled water is the key to IEUA's development of a planning scenario that can meet the uncertainties of climate change, technological changes, demand changes, import supply vulnerabilities, and other potential future challenges.

11.7 Element 5: With Whom DoesIEUA Need to Coordinate andCommunicate?

In looking at IEUA's 2009 statement describing itscurrent climate change policy, provided in Figure 11.3, it is interesting to note that every single item pertains to communication.

Figure 11.3. IEUA 2009 climate change policy.

IEUA states (IEUA, 2010) that its current approach to climate changes includes

1. Proactively working with state policymakers and legislators to target incentives in support of our energy-saving and water-saving projects
2. Working with the ACWA to encourage federal and state policy to incentivize and provide financial assistance for local resource investment in conservation and water use efficiency, recycling, and renewable energy
3. Working with the SAWPA to develop integrated, regionally coordinated water resource plans and projects that can be implemented on a watershed basis and that are eligible for Department of Water Resources funding
4. Using the "First Thursday" Prado Basin Planning Process to work with local stakeholders, such as regulators, communities, developers, and recreation and environmental interests, to implement new stormwater programs in a cost-effective way that reduces runoff from hard surfaces and promotes groundwater infiltration and water quality improvement
5. Working with several southern California alliances, including the CASA and the CWCCG, to maintain active and consistent involvement with the state's Air Resources Board, as they develop and implement the AB 32 Scoping Plan and regulations
6. Promoting AB 32 implementation measures that ensure that wastewater agencies receive credit for early, voluntary reductions in GHG emissions; are able to participate in the production and exchange of renewable energy credits under a proposed cap-and-trade system; and are treated fairly under proposed mandatory GHG reporting regulations and fee systems
7. Working with the MWD on planning efforts such as the Integrated Regional Planning process and preparing technical tools and decision-support models for incorporating climate change uncertainties into the water planning process

Source: IEUA, 2008.

11.8 Lessons Learned from the IEUA Case Study

IEUA decided early on that it needed to look at its situation—exponential growth in demand and a limited, regulated supply—in a new way. It used the following ideas to develop a system that will grow and change over time regardless of how climate change and other uncertainties play out.

1. *Donot assume anything.* IEUA developed a way to turn a limited and impaired resource—the Chino Basin—into a more reliable and higher-quality supply source that can grow as needed and provide interannual storage for dry years. By using recharge and desalinization as management tools, the Chino Basin is now a much more robust and flexible supply source for the region.

2. *Develop strong relationships with other players.* The ability to manipulate the Chino Basin is possible because of the countlessagreements developed by IEUA with every other player in the Chino Basin (and a few beyond!), and working effectively with relevant state regulators to expand the utility's water management options. Without these legal and regulatory agreements, no manipulation of the basin (e.g., groundwater recharge with reclaimed water) would be allowed.
3. *Maximize the use of recycled water in all its forms.* IEUA plans include a wide variety of places from which water can be collected, including all of its wastewater plants and additional stormwater collection basins, and ways to use water again and again, including basin recharge, distribution systems, and identification of potential users and sales to these users. IEUA also pays close attention to the sale of biosolids, alternative energy options, and energy costs to ensure the fiscal responsibility of its water reuse program.
4. *Take advantage of financial offers.* The State of California, the federal Bureau of Reclamation (USBR), and the MWD have provided incentives for utilities to develop water reuse and other local resources. IEUA jumped on these opportunities and capitalized on the significant financial savings.

Part III

Technical Information on Climate Change and Water Sector Planning

This portion of the report consists of several chapters that provide technical information regarding an array of topics relevant to understanding climate change science and modeling, and to water sector adaptation planning in the context of climate change. The material provided in Part III is intended to supplement the basic information offered in Part I, by providing more in-depth coverage of the topics and issues raised there.

The Part III chapters may be viewed as tutorials on their respective subject areas. They provide more technical depth on the subject matter than the abbreviated and more general material in Part I. Nonetheless,in most cases these chapters are not comprehensive dissertations on their particular topic area. For example, several volumes could be written (and have been) on climate science and the modeling of global climate change. Instead, our intent is to provide you, as a W/WW professional, with a solid, easy-to-understand foundation forthe practical aspects of each technical area. We also point you toward where you can learn more, if you are interested in greater depth and detail.

The chapters are as follows:

- **Chapter 12:Basics of Climate Change Modeling and GCMs**covers the basics of climate change science and modeling. It describes how climate change projections are developed, using Global Climate Models, sometimes referred to as General Circulation Models (for which the GCM acronym also applies), coupled with various scenarios for how GHG emissions may grow over the 21st century. The range of projected outcomes generated by different combinations of GCMs and emissions scenarios is discussed, as are uncertainties in the projected changes in climate.
- **Chapter 13:How to Access and Interpret Downscale Data** describes approaches available for "downscaling" GCM outputs to a smaller geographic scale as relevant for W/WW utilities. The advantages and limitations of the various approaches are also described. A discussion on how to access and interpret publicly available data derived for downscaled climate change projections is also provided. In specific, this chapter describes the "Bias Corrected Statistical Downscaled" (BCSD) data generated by Maurer et al. (2007), which reflects work funded and developed jointly by the USBR and Lawrence Livermore Laboratories. These data cover the entire United States, and are accessible through the web.
- **Chapter 14: High Probability Climate Changes** provides a summary of what scientists believe to be the most likely outcomes and impacts of climate change, and how these may vary across broad regions of the United States. This provides a useful summary of the basic changes in climate that most GCMs predict consistently, and in which climate scientists generally have the greatest confidence.
- **Chapter 15: Following Climate Changes to Potential Impacts on Utilities**complements Chapter 3 by providing a discussion of the pathways that connect changes in climate to their potential impacts on W/WW utilities. These are

discussed first as those impacts that are direct and those impacts that are indirect. A summary of potential regional impacts with links to more color maps of impact is also provided. Chapter 15 also provides a series of flow diagrams (as discussed in Part I)—one set specific to water supply utilities, and another for wastewater and storm water management agencies. These flow diagrams trace how each of the key anticipated changes in climate (e.g., hotter and drier summers in most regions) will impact the environment within which utilities operate (e.g., reducing instream flows and elevating pollutant concentrations in source and receiving waters), and how these changes in the utility operating environment will in turn impact utility functions (e.g., operational challenges to meet potable standards or discharge permits).

- **Chapter 16: Tools for Identifying Potential Climate Change Risks and Vulnerabilities** helps planners take their knowledge of potential impacts and quickly identify which of these impacts represent potential risks for their utility. The chapter provides a primer on "risk" and then provides a series of flow charts that can be used by utilities as a tool for climate change risk identification. Once the potential risks have been identified, a simple tool is provided for characterizing those risks.
- **Chapter 17: Decisions Support Tools** looks at the tools available for using the information you have gathered in your decision-making. The discussion includes a review of the most common DSTs as well as the pros and cons of each.
- **Chapter 18: A Summary of Sea Level Rise (SLR) Projections and Uncertainties**discusses projections and uncertainties specific to SLR. The issues regarding the various projections of the size and pace of SLR are addressed in general (e.g., the role of melting ice sheets), and then explored with specific reference to projections of SLR for the Miami region of southeastern Florida.
- **Chapter 19: Communication Strategies** provides an overview of good communication strategies.
- **Chapter 20: Common Questions, Misperceptions, and Practical Realities**provides an overview of some common questions, misconceptions, and practical realities regarding water resource management and climate change.

Chapter 12

Basics of Climate Change Modeling and Global Climate Models

12.1 Background on Global-Scale Climate ChangeModeling

Incorporating climate change into local planning requires local- or regional-scale climate projections. The main sources of future climate projections, however, are Global Climate Models (GCMs)—complex computer models that simulate the climate of the entire earth system, typically dividing the world into coarse-resolution grid boxes hundreds of miles across. GCMs generally consist of complex sets of equations that model the atmosphere, oceans, land surface, and ice. The models simulate how solar radiation, the Earth's orbit, GHGs, pollution, and other factors interact in the Earth's climate system.

A primary input of interest for GCMs is greenhouse gas (GHG) concentrations, which determine how much incoming solar radiation is absorbed by the atmosphere in the form of heat. GHG concentrations are derived from socioeconomic emissions scenarios that posit plausible future trends in GHG emissions according to a range of assumptions about the pace and types of global population growth, economic development, and technological change. The IPCC definition of the GHG emissions input scenarios is provided in Figure 12.1.

A number of output variables are possible in GCMS; themost commonly used output variables for analysis of climate change impacts include surface air temperature and precipitation. These output variables represent averaged values over GCM grid boxes that are hundredsofmiles-across. Because these values are averaged over such large distances, they often fail to account for smaller-scale factors that affect weather and climate, such as proximity to oceans and lakes, mountain ranges, and convective thunderstorms.

IPCC, in its fourth assessment report, used data from a number of GCMs compiled in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project 3 (CMIP3) multimodel dataset. CMIP3 is basically an archive of selected output variables from 23 of the world's most respected GCMs.[2]The outputs from these models can vary considerably across models and even among multiple runs of the same model (known as ensembles). But the selection of a socioeconomic scenario (i.e., GHG emissions and concentrations) produces even greater variation in output values. Despite the uncertainty associated with GCM projections, they are the best information available on how global (and, in particular, regional) climates are projected to change in response to elevated GHG concentrations.

[2] These models are based in Australia, Canada, China, France, Germany, Italy, Japan, Korea, Norway, Russia, the United Kingdom, and the United States of America.

A1. The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in midcentury and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI) ornonfossil energy sources (A1T), or a balance across all sources (A1B) (where *balanced* is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies). The A1B scenario generates middle-of-the-road GHG emissions.

A2. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change aremore fragmented and slower than in other storylines. The A2 scenario generates the highest GHG emissions.

B1. The B1 storyline and scenario family describe a convergent world with the same global population, whichpeaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. The scenario is also oriented toward environmental protection and social equity, and it focuses on local and regional levels. The B2 scenario generates the lowest GHG emissions.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1, and B2. All should be considered equally sound.

The Special Report on Emissions Scenarios (SRES) does not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Figure 12.1.Emission scenario definitions from the IPCC SRES.

Source: Based on IPCC, 2007b.

12.2 Downscaling—Developing Climate Change Projections on a Local and Regional Scale

When climate change is incorporated into local planning, higher resolution output than that available from GCMs is often required. To overcome the coarse resolution of GCMs, modeled outputs can be "downscaled" via one of three basic approaches:

- *Simple downscaling* involves adding projected changes in temperature and precipitation from GCMs to weather observations for a historical control period. This preserves observed spatial differences and locally observed seasonality of weather. However, this method does not account for differences in climate change within a grid box.
- *Statistical downscaling* involves correlating the observed climate record, even at the level of individual weather stations, with GCM projections for the instrumental period. These correlations are then applied to GCM projections of future climate to yield climate projections that are sensitive to geographic variability. Although statistical downscaling is computationally easier than dynamic downscaling (described next), it does not allow for changes in the relationship between the variables predicted by GCMs and local climate.
- *Dynamic downscaling* uses regional climate models (RCMs) to give higher-resolution projections than GCMs. RCMs are like GCMs, but simulate only a portion of the globe and can therefore have much smaller grid boxes than GCMs and can incorporate sub-GCM-grid scale variables (e.g., mountain ranges, lakes). RCMs are nested within GCMs using boundary conditions from GCMs to drive them. RCMs typically have resolutions of 30 miles or less. RCMs have the advantage of simulating dynamic relationships between climate variables, but require extensive computing power; that is, they are expensive to build and to run.

All three downscaling approaches yield projections at a scale more useful for local planning, but all must use GCM outputs. A key limitation of all downscaling methods is that if the GCMs do not accurately project changes in climate, then the downscaling options will typically not improve the projections. Increasing the resolution of climate projections does not increase their accuracy, but this is a common misperception. By adding an additional analytical or modeling layer to the GCMs, the downscaled results can have a higher (compounded) level of uncertainty associated with them. Nevertheless, the higher-resolution output from downscaling GCMs can be very useful if applied appropriately and with sufficient attention to uncertainty. For example, a GCM will not pick up the small-scale variations in climate that are typically seen in coastal and mountainous areas. For example, the rainfall estimates in Florida are generally considered to be off as they do not take into account the convective nature and local impacts of rainfall in this area. Downscaling can simulate these small-scale changes.

A very important aspect in analyzing the potential impact of climate change is to consider a plausible, but wide range of potential changes in climate. Basically, in all regions there is uncertainty about how much climate will change (e.g., how much temperature or sea level will rise), and for some key variables such as average annual precipitation, there is often uncertainty about whether they will increase or decrease (or how seasonal changes will happen). Scenarios that do not capture a reasonable range of uncertainty may misinform

decisionmakers. For example, if it is uncertain whether precipitation will increase or decrease and scenarios only have increases, then decisionmakers may incorrectly deduce that their planning should only consider a precipitation increase. The best way to get information on potential ranges of climate change is to examine projections for a given region from the full suite of climate models used by the IPCC.

A further discussion of how to access and utilize publically available downscale data sets is provided in the next chapter.

Chapter 13

How to Access and Interpret DownscaledData

Many organizations want to access downscaled climate data for use in analyzing the impact of climate change specific to a given watershed or municipality. It is important to understand that downscaled data arealways derived from larger-scale GCMs. Downscaled data arecommonly available in 1/8° resolution, or grid boxes approximately 14 km (8 miles) on a side. But thesedownscaled data arederived from GCMs typically at 2° resolution, or grid boxes 220 km (140 miles) on a side. Although downscaled climate data areat a higher resolution than GCM data, they are not more accurate. In fact, quite often the opposite is the case: the mathematical processes necessary to express GCM grid boxes as 1/8° grid boxes can actually increase uncertainty. This does not mean that downscaled climate information is useless, but it does suggest that some care be exercised in drawing conclusions about climate change at small spatial scales.

This chapter discusses only two sources of downscaled data because they are readily available and free to the public. Other techniques exist, such as statistical downscaling, as do other tools, such as SimCLIM. However these techniques and tools are either methodologically complex or proprietary. Consequently, we focus on a detailed analysis of freely available downscaled climate data. We touch briefly on the North American Regional Climate Change Assessment Program (NARCCAP), which downscales climate data to 50-km grid cells. But we treatbias-corrected and spatiallydisaggregated BCSD datasets in greater depth because theydownscale to higher-resolution 1/8° grid boxes that are more relevant at the scale of a watershed or municipality.

Dynamically downscaled RCM output has recently been made available through the NARCCAP (2010). NARCCAP is producing high-resolution (50-km grid cells) climate output suitable for regional climate change impact analysis for a range of GCM–RCM combinations covering the entire coterminous United States. The baseline period is defined as 1971–2000 and projections are available for 2041–2070. The output of RCMs are considered more “accurate” than other downscaling methodologies because they take GCM output and run it through a more refined model of regional climate. This allows RCMs to capture regional weather phenomena that are often missed in GCMs, but critical for understanding water resources. But even at 50 km, this scale may be too big for many water utility purposes. Furthermore, no matter how “accurate” a RCM is, it fundamentally relies on GCM output. This means that any uncertainties in the GCMs cascade through the RCMs as well. Therefore, RCMs are not a magic bullet. But they do indicate a trend of increasing the resolution of climate models. It may take some years to realize the promise of this increased resolution, however the NARCCAP output is available now for use.

An excellent source of *spatially downscaled* climate change projections for monthly temperature and precipitation, at 1/8° spatial resolution for the 48 contiguous United States (and parts of Canada and Mexico)[3] is a public access archive hosted by USBR and Lawrence

[3] Coverage includes the North American Land-Data Assimilation System domain, spanning 25.125°N to 52.875°N and -124.625°E to -67.000°E.

Livermore National Laboratory [http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/,Maurer et al. (2007),hereafter referred to as the Maurer archive, method, or dataset].[4]

Basically, Maurer's method uses historical climate data to calibrate the coarse GCM output and then uses correlations developed from historical data to correct for spatial variation in climate at the finer 1/8° scale. The Maurer archive uses GCM projections referenced in the IPCC Fourth Assessment Report, also known as CMIP3; see Meehl etal., 2007b). The Maurer archive contains 112 fine spatial resolution translations of 16GCMs from CMIP3 and three socioeconomic scenarios that reflect widely different GHG emissions levels into the future. Some GCMs were run multiple times and some GCMs were run more times for certain scenarios; each "run" produces a distinctly different time series projection. Consequently, there are 39 GCM translations for scenario A1B,[5] 36 for scenario A2,[6] and 37 for scenario B1.[7] A user can select a customized subset up to all 112 model/scenario/run combinations according to their purposes. Without a good reason to select a subset of these 112 translations, we recommend using them all as a greater range of projections provides greater insight into the uncertainty associated with the projections.

13.1 Accessing the Maurer BCSD Archive for Downscaled Climate Change Projections

As noted, the Maurer downscaled results are available from a public access archive hosted by USBR and Lawrence Livermore National Laboratory. Access is found at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/. The public access archive has a "Data: Subset Request" tab that allows anybody to request a dataset from the archive. Once the dataset has been downloaded, intense post processing of the data files in Excel or a similar program is necessary for a variety of purposes. For example, the downloaded files provide total projected temperature and precipitation values for future time periods. These values must be subtracted from baseline values to generate values for change in temperature and precipitation. The dataset request is defined using the following steps:

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[4] This dataset is also commonly referred to as the BCSD dataset. We use "Maurer" here because it refers to the specific source of the data and not just the methodology.

[5] The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in midcentury and declines thereafter, and the rapid introduction of new and more efficient technologies (Nakićenovic et al., 2000). The A1B scenario is often considered a "middle of the road" scenario.

[6] The A2 storyline and scenario family describes a very heterogeneous world. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines (Nakićenovic et al., 2000). Of the three scenarios applied by Maurer, A2 has the highest GHG emissions.

[7] The B1 storyline and scenario family describes a convergent world with the same global population,which peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies (Nakićenovic et al., 2000). Of the three emissions scenarios applied by Maurer, B1 has the lowest GHG emissions.

1. Select the desired variables, either precipitation rate and/or surface air temperature.
2. Select emissions scenarios, climate models, and runs up to all 112 combinations.
3. Select a time period between January 1950 and December 2099.
4. Select a spatial extent for the data. This can be a single 1/8° location or a larger region in 1/8° increments.
5. Select the type of analysis required of the data. This can include no analysis to receive only the data time series or period or spatial averaging (note that the archive will not provide both period *and* spatial averaging—to do this, one must download the raw data time series for a customized analysis).
6. Select an output format of NetCDF or ASCII text, comma-delimited (csv).
7. Select additional available data products, including 1/8° or 2° observed data (1950–1999), 2° raw GCM data, and/or 2° bias-corrected GCM data.

If you elect to receive the data as period averages, theywill be delivered as a separate file for each variable, each model/scenario/run combination, and for both the mean and the standard deviation. If you use all 112 combinations and both variables, this would mean 448 individual files. This many files require some effort to compile in a usable form. Keep in mind that by period averaging, all seasonal variation in the monthly time series will be lost.

However, if you elect to receive the data as a spatial average, it will be delivered as two files per variable—separate files for the average and the standard deviation for each variable. Each file will include all selected years and months as the rows and all selected model/scenario/run combinations as columns. If you use all 112 combinations and both variables, this willmean four individual files, which greatly reduces the effort required to compile the information and provides more flexibility for analysis.[8]

We recommend that the most effective use of the archive is to download the spatially averaged data for a specified location for all time periods of interest. Typically, this means downloading two or more future periods of interest as well as a baseline hindcast. Keep in mind that because of climate variability from one year to another, it is typically unwise to use a single year or even a small number of years to define future climate periods or the baseline hindcast. We suggest using periods no shorter than 10 years, and preferably 20 years or more centered around the year of interest. This increases the climate change signal and reduces the noise of model-simulated natural climate variability.

For example, a study might be interested in climate change in the year 2035. We recommend requesting monthly projections of a period spanning January 2025 through December 2044 and period averaging to define the 2035 projection. Such a period average could be done on the yearly averaged data, on a monthly basis across years (e.g., average all January temperatures), or by multimonth seasons across years according to the purposes of the study. Most studies, however, prefer a change from current conditions, as opposed to absolute temperature and precipitation values at some future year. Consequently, we suggest defining a baseline hindcast period to download from the archive as well. A baseline of the year 2000

[8] The greatest flexibility for analysis is maintained by downloading the raw time series data with no spatial averaging, but as most climate change impacts or vulnerability studies define a given geographic area of interest, e.g., a watershed or a county, downloading the spatially averaged data is usually adequate for analytical purposes.

might include a similar period average from January 1990 through December 2009. To determine changes over time instead of absolute values, subtract the baseline hindcast values from the future projection values. We recommend expressing these changes as degree change over baseline for temperature and percent change over baseline for precipitation.

13.2 Maurer Results for the City ofMiami

Stratus Consulting used the bias-corrected and spatially downscaled climate projections derived from CMIP3 data and provided at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/ described by Maurer et al. (2007) to determine projected climate change in temperature and precipitation for the city of Miami. Stratus Consulting requested projections of monthly absolute temperature and precipitation rates for three selected time periods: 1970–1999, 2050–2069, and 2080–2099. The projections were derived from the full complement of all available data in the Maurer dataset, including all 112 different model/scenario/run combinations. The data were delivered as a spatial average offour 1/8 grid cells that encompass a majority of the city of Miami. We then further processed that data to period average for all three time periods both for monthly averages (see Table 13.1) and annual averages (see Table 13.2). To determine changes over time instead of absolute values, we subtracted the 1970–1999 values from the 2050–2069 and 2080–2099 projections, expressed as degree change over baseline for temperature and percent change over baseline for precipitation.

The annual average temperature results in Table 13.2 indicate that Miami is projected to warm approximately 2 to 3 °F by 2060 and approximately 3 to 5 °F by 2090. These ranges indicate the uncertainty associated with future GHG concentrations that are due to divergent future global socioeconomic development patterns. The monthly temperature results in Table 13.1, however, indicate that under all three scenarios temperatures warm more in the summer months than in the winter months for both 2060 and 2090. Despite all of the inherent uncertainties in climate projections, the consistency of warming across all scenarios, all months, and all future time periods lends weight to the conclusion that a warmer future is in store for Miami. Agreement among model averaged scenarios on the seasonal difference in warming is compelling, but further analysis ofintermodel agreement on this seasonal change is warranted before any firm conclusions are drawn.

The annual average precipitation results in Table 13.2 show a mixed picture for Miami. Scenario B1 indicates minor precipitation increases in both 2060 and 2090 and scenarios A1B and A2 indicate approximately a 1 to 2% precipitation decrease in 2060 and approximately a 3 to 5% precipitation decrease in 2090. The monthly precipitation results in Table 13.1, however, indicate that under all three scenarios precipitation is projected to decrease moderately in January through August and increase significantly in September through December. Despite differences in projected annual precipitation changes, the pattern of seasonal precipitation changes is consistent across all three scenarios. It should be noted that changes in precipitation are much more uncertain than changes in temperature and are not uniform in directionality (i.e., some models indicate a precipitation increase and others a decrease). Thus, it is even more important to consider the range of projections among the models through statistics such as standard deviations across model averaged scenarios. Again, agreement among model averaged scenarios on the seasonal difference in precipitation is compelling, but further analysis ofintermodel agreement on this seasonal change is warranted before any firm conclusions are drawn.

Table 13.1. Projected Monthly Changes for Miami, FL (as Derived from Maurer Dataset)

	Change from 1970 to 1999 for Scenario B1 (Precip.: %; Temp.: °F)				Change from 1970 to 1999 for Scenario A1B (Precip.: %; Temp.: °F)				Change from 1970 to 1999 for Scenario A2 (Precip.: %; Temp.: °F)			
	2050–2069		2080–2099		2050–2069		2080–2099		2050–2069		2080–2099	
	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.
Jan	-0.76	1.77	0.87	2.21	-2.44	2.29	-5.19	3.31	-3.74	2.33	-3.11	4.22
Feb	-1.67	1.87	0.18	2.34	-7.88	2.48	-7.14	3.63	-6.43	2.54	-11.30	4.36
Mar	-7.56	2.03	-7.20	2.81	-12.21	2.96	-12.69	4.13	-15.79	2.84	-22.67	4.88
Apr	-6.46	2.18	-5.27	3.02	-7.35	3.06	-17.39	4.35	-6.82	3.15	-22.16	5.21
May	-5.36	2.30	-5.31	2.96	-9.52	3.30	-12.24	4.45	-11.61	3.19	-18.23	5.44
Jun	-4.41	2.44	-6.39	3.07	-9.90	3.41	-13.20	4.63	-11.79	3.40	-18.40	5.67
Jul	-6.36	2.49	-7.43	3.16	-8.30	3.47	-11.52	4.67	-8.14	3.45	-14.86	5.75
Aug	-6.95	2.62	-6.72	3.20	-8.89	3.55	-9.49	4.75	-6.08	3.44	-12.11	5.79
Sep	4.07	2.42	4.06	3.00	1.73	3.30	1.23	4.50	1.71	3.25	0.54	5.43
Oct	13.20	2.34	17.31	2.88	24.07	3.13	24.51	4.44	16.76	3.12	26.59	5.30
Nov	12.69	2.27	15.84	2.92	12.40	3.19	17.56	4.47	13.60	3.15	21.29	5.43
Dec	12.81	2.19	11.71	2.67	9.61	3.00	6.67	3.97	7.51	2.81	5.43	4.71

Table 13.2. Projected Annual Average Changes for Miami, FL (as Derived from Maurer Dataset)

	Change from 1970 to 1999 (Precip.: %; Temp.: °F)			
	2050–2069		2080–2099	
Scenario	Precip.	Temp.	Precip.	Temp.
B1	0.10	2.23	0.64	2.84
A1B	-1.20	3.08	-2.76	4.26
A2	-2.30	3.05	-5.11	5.17

Chapter 14

High-Probability Climate Changes

This chapter provides a summary of what scientists believe to be the most likely outcomes and impacts of climate change and how these vary across broad regions of the United States. This overview of the climate change predictions in which scientists have the greatest confidence may be sufficient to indicate what W/WW utility planners need to know to take initial steps in their climate change assessments and adaptation planning.

14.1 Increasing Temperature

There is a consensus that GHGs produced by human activities have already caused an increase in global mean temperature. Indeed, there is no other plausible explanation for the increased temperature;i.e., there is no natural cause that explains the warming (IPCC, 2007a). Increases in carbon dioxide (CO_2) and other GHGs resulting from human activities traps energy from the sun in the atmosphere that would otherwise be dissipated back into space. This has contributed to an increase of about 0.74 °C (1.33 °F) in global average temperature since 1900.

This warming trend is expected to accelerate as more and more GHGs are added to the atmosphere. By 2100, the additional rise in global average temperature is projected to be in therange of 1.1 to 6.6 °C (~ 2–12 °F) above 1990 levels. There is little doubt that this warming would continue for a long period into the future, even if it were possible to suddenly and drastically reduce GHG emissions.

The range ofestimates of the degree of warming that will occur between now and 2100 reflects the state of knowledge on future development paths across the world and the science of climate change. Two key uncertainties stand out.

1. Modeling climate in 2100 requires input assumptions regarding the rate of growth of GHG emissions. These reflect uncertainties about future development paths including population growth, economic growth and technological changes.
2. There is also uncertainty about how much warming will happen with a given concentration of GHGs. For example, the IPCC concluded that there is a two-thirds chance that global temperatures will rise 2 to 4.5 °C with a doubling of CO_2 levels in the atmosphere, and a corresponding one-third chance the warming could be lower or higher than that range.

It is not surprising, therefore, that the major climate models produce varying estimates of both CO_2 concentrations and global mean temperature. In the end, however, they all confirm the warming trend and predict it will accelerate within the next few decades.

14.2 Increasing Evaporation and Precipitation

One of the simplest ways to envision the effect of global warming on water resources is to follow the logic of what happens when temperatures increase.Global warming will basically accelerate the pace of the hydrologic cycle. Higher air temperatures will cause water to evaporate more readily, more water vapor to be in the atmosphere, and the total amount of precipitation at a global level to increase. This accelerated hydrologic cycle is logically projected to result in an overall increased intensity of rainfall events. Consistent with the fact that global warming has already been occurring during the last century, precipitation records show that total global precipitation (and precipitation over the United States) has increased and storms have become more intense.

In contrast to these consistent predictions of the effect of warming on the total amount of precipitation globally, forecasts of the amount of precipitation vary greatly from one region to another. Areas in the high latitudes and some wet tropics are generally expected to see increased precipitation, and dry regions in the midlatitudes and the dry tropics are generally expected to see decreases in total precipitation.

At one extreme, higher temperatures imply that areas subject to drought may see more extensive drought and heat wave events;at the other extreme, areas accustomed to snowfall will see warmer winters. Warmer and shorter winters are already implicated in the reduction in the amount of water stored as ice in glaciers, and in seasonal snowpacks. The shorter cold season means that the spring melt can arrive much earlier and hassignificant implications foravailable downstream flows in late summer and early fall. However, it is also quite possible that where it is cold enough to snow, the amount of snowstorms can increase. This could mean a more rapid buildup of the snowpack and itsearlier and faster melting in the spring.

14.3 Rising Sea Level

With higher temperatures, the oceans expand (because water expands when heated) and glaciers and ice sheets melt, causing sea level to rise. Sea level is projected by the IPCC to rise from 0.2 to 0.6 m by 2100. This assumes no catastrophic losses of either the Greenland or Antarctic ice caps. Studies thataccount for such melting find that rates ofSLR could be as much as 1 m by 2100 and possibly up to 2 m. Some scientists suggest that the most likely SLR by 2100 is 0.8 m (2.5 feet).

Chapter 15

Going fromClimate Changes to Potential Impacts on Utilities

It is important to distinguishbetween processes of climate change and the impacts onand implications forwater suppliers that result from these changes. In fact, it has become commonplace to mix discussion of the basic processes of climate change, for which there is good evidence documenting changes already underway (e.g., temperature rise), with the discussion of impacts that are more remote and uncertain in terms of both the chain of causation and timing. Weaving the story together in this way can add to information overload and leave theimpression that impacts are already occurring at full strength when, in fact, their onset is still unfolding. The incidence of any given impact may come about as a threshold effect, as a tipping point phenomenon, or as a smooth gradient. Recent extreme events such as droughts or floods may support a belief that impacts are already upon us. As this may be the case, the worst may still be yet to come. We therefore need to understand much more about the cause and effect relationships that produce these impacts.

To emphasize these distinctions, this discussiondistinguishesbetween direct impacts, indirect impacts, and compound impacts.

15.1 Direct Impacts

Direct impacts are defined as impacts resulting from the effects of climate change on water utility functions and operations. Figures 15.1 through 15.4 present climate change causation checklists. These checklists provide, for each category of potential climate changes, a summary of potential changes and the associated direct impacts. Climate change causation summary tables are provided for utilities in the mountain West, the Southwest, the humid East/Midwest, and coastal areas of the United States. A number of similarities are evident across regions, but there are distinct differences also. In addition, the coastal checklist could be merged with any of the others whenever larger regions encompass both types of conditions.

The impacts on these lists are not expected to emerge all together or at once. As discussed previously, there are gradient functions, threshold effects, and conceivably many other influences involved in the chain of causation that will stretch impacts over time. With many climate scientists predicting an accelerating pace of change over the next several decades, these prospective impacts have meaning for today's mid-tolong-term (20–50 year) planning. We have every reason to believe that these impacts are coming toward us. But utility planners will have to grapple with many of them prospectively rather than as phenomena that are already observable, except at the leading edge of the trend.

1. **Warmer and shorter winter seasons**
   - More rain, more rainonsnow, and earlier spring snowmelt
     - Altered recharge of groundwater aquifers
     - Earlier runoff into surface waters
       a. Lower summer/fall base flows in surface waters
2. **Warmer and potentially drier summer seasons**
   - Changes in vegetation of watershed and aquifer recharge areas
     - Altered recharge of groundwater aquifers
     - Altered quantity and quality (e.g., TOC, alkalinity) of runoff into surface waters
     - Changes to vegetation from fire and pests
   - Increased water temperature
     - Increased evaporation and eutrophication in surface sources
     - Water treatment and distribution challenges (disinfection, byproducts, regrowth)
   - Increased water demand
     - Increased irrigation demand in longer growing season
     - Increased urban demand with more heat waves and dry spells
     - Increased drawdown of local groundwater resources
3. **More intense rainfall events**
   - Increased turbidity and sedimentation
     - Loss of reservoir storage
       a. Shallower, warmer water; increased evaporation and eutrophication
       b. Potential conflicts with flood control objectives
     - Water filtration or filtration/avoidance treatment challenges
   - Increased risk of direct flood damage to water utility facilities

Figure 15.1.Climate change causation checklist for utilities in the Mountain West.

1. **Warmer and probably drier overall with more extreme droughts and heat waves**
   - Likely reduced quantities of surface water available from local runoff
   - Likely reduced quantities of water available to recharge groundwater aquifers
   - Very likely increased evaporative losses in interbasin transfers of surface waters
   - Changes in vegetation of watershed and aquifer recharge areas; more fire and pests
     - Altered recharge of groundwater aquifers
     - Altered quantity and quality (e.g., TOC, alkalinity) of runoff into surface waters
   - Increased water temperature
     - Increased evaporation and eutrophication in surface sources
     - Water treatment and distribution challenges (disinfection, byproducts, regrowth)
   - Increased water demand
     - Increased irrigation demand
     - Increased urban demand with more heat waves and dry spells
     - Increased drawdown of local groundwater resources
     - Increased difficulty of maintaining minimum in-stream flows in surface waters
2. **More intense rainfall events**
   - Increased turbidity and sedimentation
     - Loss of reservoir storage
       a. Shallower, warmer water; increased evaporation and eutrophication
       b. Potential conflicts with flood control objectives
     - Water filtration or filtration/avoidance treatment challenges
   - Increased risk of direct flood damage to water utility facilities
3. **Vegetation changes**
   - More frequent fires
     - Runoff of sediment, debris
     - Faster snowmelt
   - Pest Infestations
     - Runoff of sediment, debris
     - Faster snowmelt

Figure 15.2. Climate change causation checklist for utilities in theSouthwest.

1. **Warmer overall and possible increases in annual precipitation**
   - More rain with seasonal shift
     - More rainfall in winter and late spring
     - Potentially less rainfall in late summer and fall with more extreme droughts
       a. Lower summer/fall base flows in surface waters
   - Changes in vegetation of watershed and aquifer recharge areas
     - Altered recharge of groundwater aquifers
     - Altered quantity and quality (e.g., TOC, alkalinity) of runoff into surface waters
   - Increased water temperature
     - Increased evaporation and eutrophication in surface sources
     - Water treatment and distribution challenges (disinfection, byproducts, regrowth)
   - Increased water demand
     - Possible increased urban demand during drought periods
2. **More intense rainfall events**
   - Increased turbidity and sedimentation
     - Loss of reservoir storage
       a. Shallower, warmer water; increased evaporation and eutrophication
       b. Potential conflicts with flood control objectives
     - Water filtration or filtration/avoidance treatment challenges
   - Increased risk of direct flood damage to water utility facilities

Figure 15.3. Climate change causation checklist for utilities in thehumid East, Southeast, and Midwest.

1. **Rising sea levels**
   - Increased saline intrusion into groundwater aquifers
     - Water treatment challenges: increased bromide; need for desalination
   - Increased salinity of brackish surface water sources
     - Water treatment challenges: increased bromide; need for desalination
2. **Warmer overall**
   - Altered discharge characteristics of major rivers that are due to upstream changes
   - Altered recharge characteristics of major groundwater aquifers that are due to upstream changes
   - Increased water temperature
     - Increased evaporation and eutrophication in surface sources
     - Water treatment and distribution challenges (disinfection, byproducts, regrowth)
   - Possible increased water demand
     - Increased irrigation demand
     - Increased urban demand with more heat waves and dry spells
     - Increased drawdown of local groundwater resources
3. **Increased risk of direct storm and flood damage to water utility facilities**
   - Altered discharge characteristics of major rivers that are due to upstream changes
   - Altered recharge characteristics of major groundwater aquifers that are due to upstream changes
   - Increased water temperature
     - Increased evaporation and eutrophication in surface sources
     - Water treatment and distribution challenges (disinfection, byproducts, regrowth)
4. **Possible increased water demand**
   - Increased irrigation demand
   - Increased urban demand with more heat waves and dry spells
   - Increased drawdown of local groundwater resources
5. **More intense rainfall events**
   - Increased turbidity and sedimentation
     - Loss of reservoir storage
       a. Shallower, warmer water; increased evaporation and eutrophication
       b. Potential conflicts with flood control objectives
     - Water filtration or filtration/avoidance treatment challenges
   - Increased risk of direct flood damage to water utility facilities

Figure 15.4.Climate change causation checklistfor utilities in coastal regions.

The climate change causation checklists make it possible to scan the full spectrum of potential direct impacts in a one-page summary for each regional scenario that follows a simple cause–effect logic and organizes the impacts into related groups. Taken together, it is believed that these four lists provide complete coverage of direct impacts. Despite some common elements between them, it is also believed that these four lists constitute the minimum set needed to cover all the direct impacts. This first iteration of the lists is regarded as a workinprogress and refinements are invited to help improve it.This is anoncomprehensive list that should be refined and continuously updated by the user of the document.

15.2 Indirect Impacts

When we consider impacts, it is critical to remember that other changes matter too. For example, flooding will be affected by changes in peak precipitation events, winter precipitation levels, snowmelt, and other climate factors. But, it also will be affected by land use changes, such as the building of more impervious surfaces such as roads and parking lots. Water supplies will be affected by climate change. But they also will be affected by changes in population, shifts in water withdrawal and consumption, laws and regulations, and other factors. A sound analysis of climate change impacts should also consider these other important changes.

15.2.1 Climate Change Impacts Related to Water Supply

Although there is still scientific uncertainty over the pace and specific impacts of climate change, there is a growing body of scientific knowledge and a reasonable degree of consensus on several key features of the world we will face in the decades ahead. For example, there are more than 20 GCMs used by the IPCC in its recent assessment report (IPCC, 2007a), and each GCM generates somewhat different estimates of future changes in key parameters such as mean levels of annual precipitation at the regional scale. Some argue that the differences in predictions, as well as the potential for misestimation, increase when these global model outputs are scaled down to regional level forecasts. As the sage philosopher Yogi Berra once noted, "Predictions are difficult to make, especially about the future."

Although there is consensus across the GCMs in terms of global and regional predictions that temperatures will be higher as we move through the 21st century, there is variation in the mean annual precipitation forecasts. Some models suggest higher mean annual precipitation in some regions (usually the northern portions of the United States), and others predict reduced levels of annual average precipitation (especially in more southern latitudes, including the already arid Colorado River basin and other parts of the rapidly growing southwestern United States).

One key to interpreting regional forecasts is that mean annual precipitation levels are less important for water supply management than changes in precipitation patterns, including the intensity of precipitation, the number of dry days between precipitation events, and the likelihood of rain rather than snow, parameters for which the models tend to be more consistent. For example, there is a general expectation that throughout the United States (even in regions where mean annual precipitation may increase), the following types of adverse patterns may likely be evident within annual precipitation:

- Winters may be wetter than now in some locations, but summers will probably see less precipitation than enjoyed historically.
- Summers are likely to be drier than they are today in most regions because of the combination of higher temperatures, increased evapotranspiration, and decreases (or, in some regions, no change) in summer precipitation.
- Precipitation will likely fall in shorter-duration, more extreme events (rather than in the longer-duration but gentler events of the past), and the number of dry days between precipitation events is expected to increase. This means that there will be less infiltration and recharge, and more stormwater runoff and non-pointsource loading of sediments and other pollutants to watersheds and reservoirs, and higher turbidity levels at surface WTPs. This could lead to more flooding of riverside water

supply infrastructure and wastewater facilities, and more storm-related damage in general.

- Droughts are likely to occur with increased frequency, longer duration, and/or greater severity than in the past, in several already water-limited regions.
- In regions that currently rely on snowpack for their water supply (i.e., much of the western United States), more precipitation will fall as rain than as snow, and the snowpack that does accumulate will melt earlier in the year. This will create challenges for water storage, flood control, and instream flow management (i.e., peak flows will be earlier in the spring, leaving less water for instream flows over a longer, hotter, and probably drier summer and fall period).
- SLR will increase saltwater intrusion into coastal aquifers, push salt lines further up estuarine rivers (some of which currently are freshwater sources for public water supply systems), and threaten to inundate coastal infrastructure.
- An increased likelihood and/or severity of wildfires in key watershed areas—because of hotter and drier summers and enhanced opportunities for pine beetles and other destructive pests to survive and thrive in forest areas—will adversely impact the quality and quantity of surface water supplies.

As discussed in the next section, these impacts collectively point to an increased need to consider a broad range of water supply planning options, including the likely increased need forwater reuse in the future.

15.2.2 Climate-Change-Related Impacts that Will Encourage Reuse

The impacts noted earlier help frame how climate change can impact the business of public water supply. It is useful to think of how climate change can impact water agencies from source to tap. In doing so, it also is useful to consider what impacts may arise in terms of the *quantity* of water, water *quality*, and *infrastructure* safety (e.g., exposure to storm surge and flooding).

In terms of the *quantity (and timing) of water* available to water suppliers, the following are likely to contribute to a reduction in the reliable supply of traditional water source options:

- Increased dryness and drought, less snowpack, and less summer precipitation in many locations (as noted in the previous subsection).
- Lower summertime instream flows and higher water temperatures are likely to lead to a greater need to forgo potable extractions from lakes, rivers, and streams in order to provide enough flow and cooling to preserve aquatic ecosystems, including the protection of threatened and endangered species such as several varieties of salmon.
- Less reservoir storage, as a result of numerous factors. These include modified dam design and operating regimes to accommodate flood control (because of earlier snowmelt and runoff, and more extreme rain events), escalated hydropower production demands (especially as power demands escalate through hotter and prolonged summer periods), and instream flow protection (such as more summer and fall water releases to cool and enhance flows). There is also likely to be more sedimentation behind dams as a result of the increased intensity of precipitation events (especially if these occur in tandem with more forest fires or other watershed stresses).

In terms of the *quality of source and distributed water*, climate change impacts are likely to include the following:

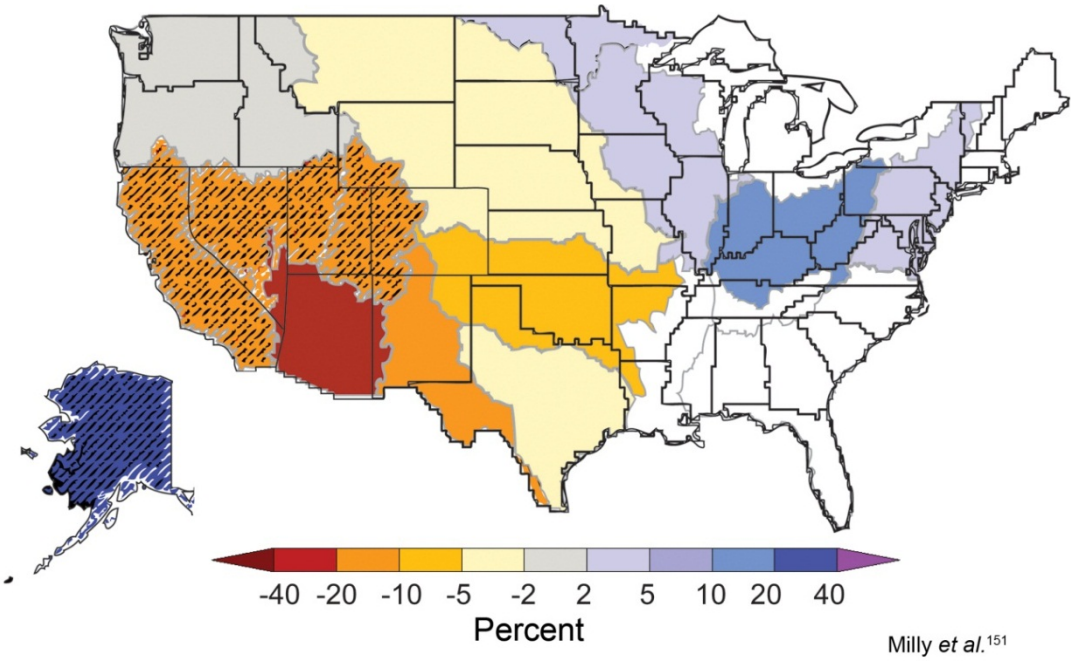
- Lower source water quality and increased variability in critical source water parameters such as turbidity (because of the anticipated increase in extreme precipitation events). The potential for more wildfires and other watershed disruptions will also lower the quality of some source waters. This general decline (and greater variability) in source water quality ultimately implies a higher cost fortreating existing supplies.
- Lower instream flows imply less dilution of wastewater and non-pointsource pollutant loadings, thus leading to lower-quality source water. This may also result in more regulatory pressure on wastewater dischargers to meet tougher National Pollutant Discharge Elimination System (NPDES) permit conditions, which in turn provides greater incentive for wastewater treatment systems to pursue water reuse in lieu of effluent discharge.
- Saltwater intrusion into coastal groundwaters and further upstream in tidal-influenced rivers will either eliminate these sources as water supply options, or require the addition of desalting to the treatment process.
- Higher temperatures (and potentially altered chemistry and pH levels) of source and finished water may well result in the elevated formation of disinfection byproducts (DBPs—regulated drinking water contaminants) and/or pose other costly treatment and operational challenges to meeting federal and state drinking water standards at the tap.

To compound the problem, the demands for water are likely to increase for many water utility customers. This is especially likely during peak summer demand periods, because elevated temperatures and the potential for less summertime precipitation imply higher outdoor irrigation demands for homes, businesses, parks, and agriculture.

Thus, in total, climate change is likely to appreciably reduce the amount of water available from existing or potential new traditional supplies, and/or it is likely to appreciably increase the cost of treating those supplies to deliverable quality. At the same time, utilities are likely to face increased peak water demands. Combined, this implies more water shortages and/or higher costs for delivering traditional supplies. These factors will make desalination, water reuse, and conservation look more cost-competitive than they do currently. Further, because of the droughtinsensitivity of desalination and reuse yields, these options provide a valuable added reliability benefit to water agencies that add these options to their water supply portfolios.

15.3 Regional Impacts

The U.S. Global Climate Resource Program (USGCRP) has produced regional projections of temperature and precipitation. Figure 15.5 illustrates the kind of information that is available at this site. You can find images for your region at http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/regional-climate-change-impacts.



Runoff, which accumulates as streamflow, is the amount of precipitation that is not evaporated, stored as snow pack or soil moisture, or filtered down to groundwater. Projected changes in median runoff for 2041-2060, relative to a 1901-1970 baseline, are mapped by water-resource region. Colors indicate percentage changes in runoff. Hatched areas indicate greater confidence due to strong agreement among model projections. White areas indicate divergence among model projections. Results are based on emissions in between the lower and higher emissions scenarios.[91]

Figure 15.5.Regional projections of changes in median runoff, mid-21st century.
Source: USGCRP, 2011b.

The USGCRP Scientific Assessment also provides the following summary of global climate change impacts in the United States:

- Climate change has already altered and will continue to alter the water cycle, affecting where, when, and how much water is available for all uses.
- Floods and droughts are likely to become more common and more intense as regional and seasonal precipitation patterns change, and rainfall becomes more concentrated into heavy events (with longer, hotter dry periods in between).
- Precipitation and runoff are likely to increase in the Northeast and Midwest in winter and spring, and decrease in the West, especially the Southwest, in spring and summer.
- In areas where snowpack dominates, the timing of runoff will continue to shift to earlier in the spring and flows will be lower in late summer.
- Surface water quality and groundwater quantity will be affected by a changing climate.
- Climate change will place additional burdens on already stressed water systems.
- The past century is no longer a reasonable guide to the future for water management.

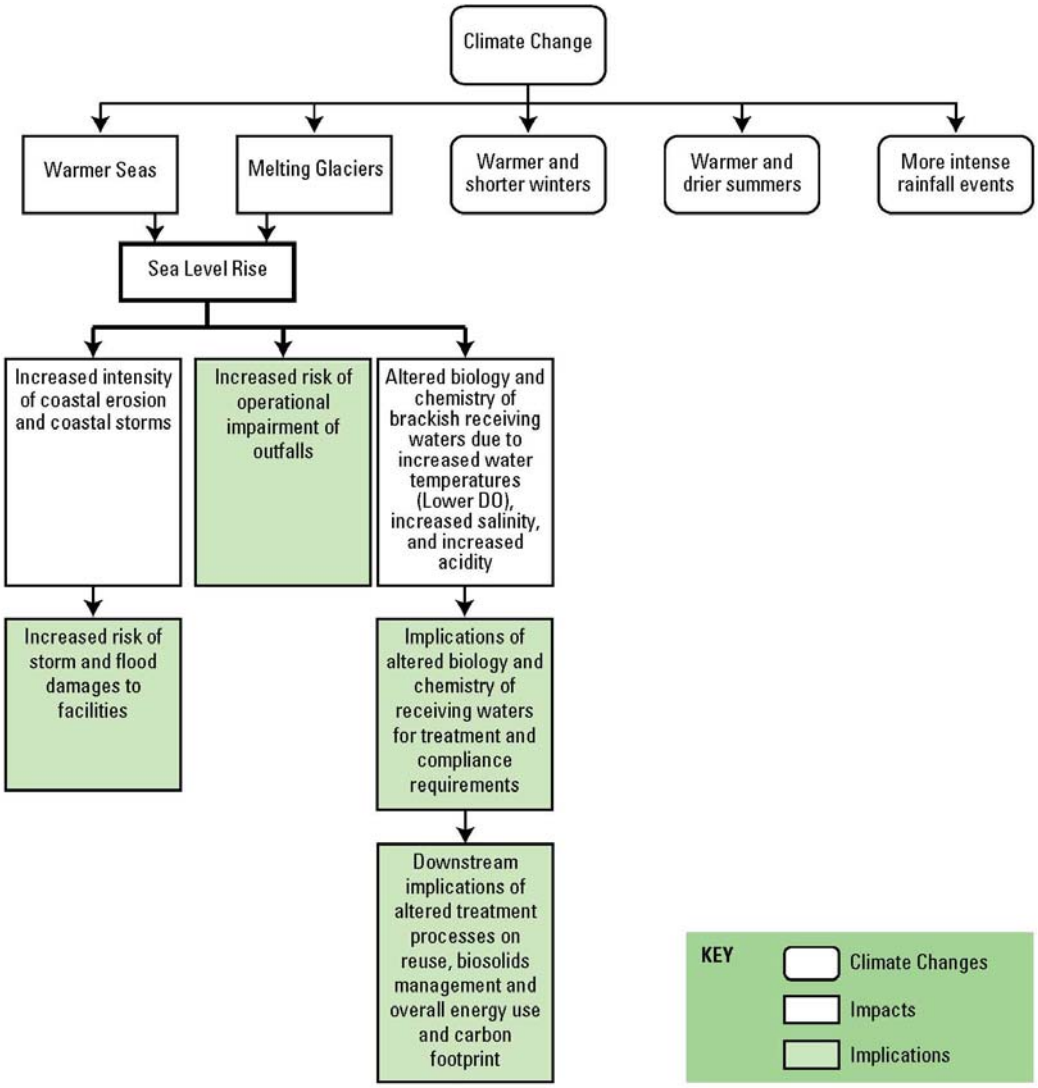


Figure 15.6.Impacts and implications of SLR for wastewater agencies.
Source: Borrowed with permission from WERF, 2010.

15.4 A Risk Identification Tool

The following section presents a series of flow diagrams—one set specific to water supply utilities and another for wastewater and stormwater management agencies, designed as a risk identification tool (Figures 15.6–15.17). These flow diagrams trace how each key anticipated *change in climate* (e.g., warmer and shorter winters) will *impact* the environment (e.g., earlier spring melt and runoff) and create *risks* (e.g., increased risk of flood damages to facilities).

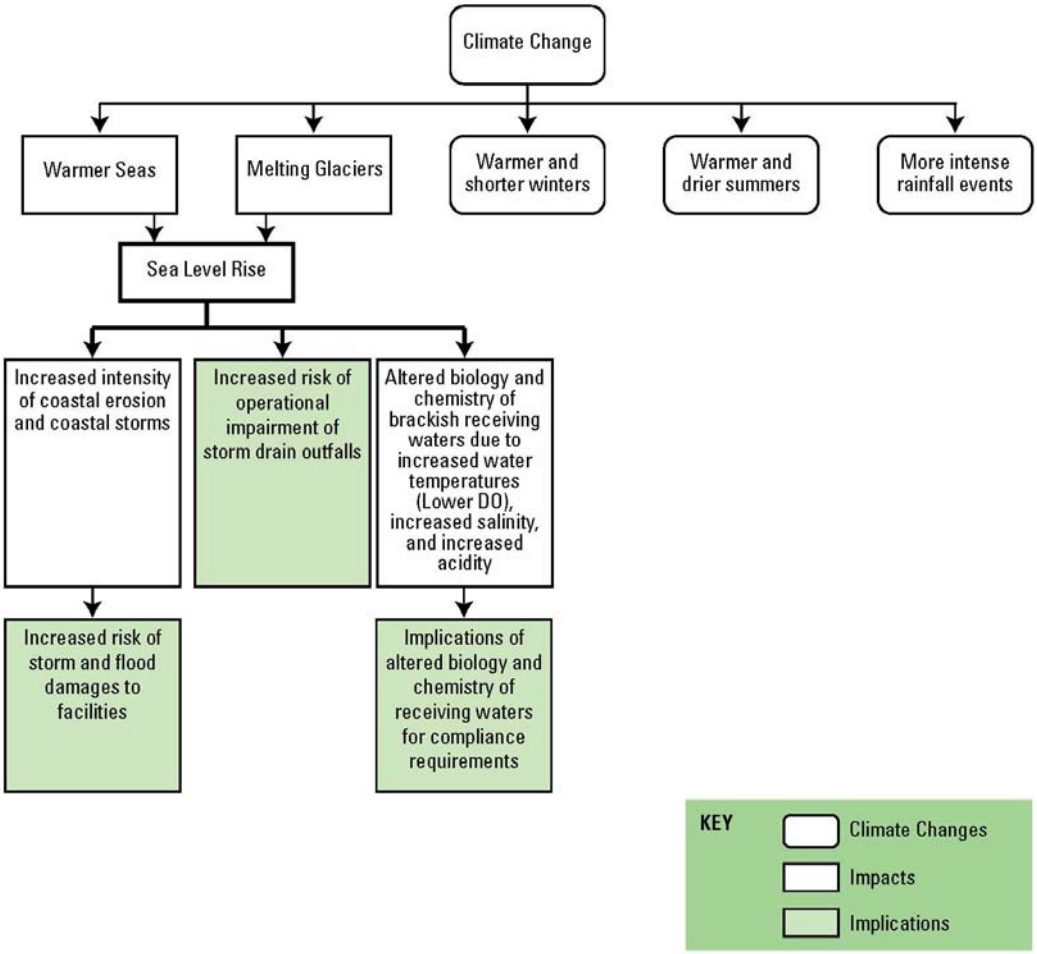


Figure 15.7.Impacts and implications of SLR for stormwater agencies.
Source: Borrowed with permission from WERF, 2010.

These flow diagrams are designed to help utilities ensure that the important risks are identified. By running through each flow diagram several times,a summary chart can be developed, providing a list of potential climate-change-related risks. Note that in the example provided in Figure 15.18, the hypothetical utility followed the warmer and shorter winters flow diagram. However, the utility knew that recharge of groundwater aquifers would never be an issue for it, as all its water is supplied from surface sources. Therefore, its final risk identification list does not identify any risks to aquifers.

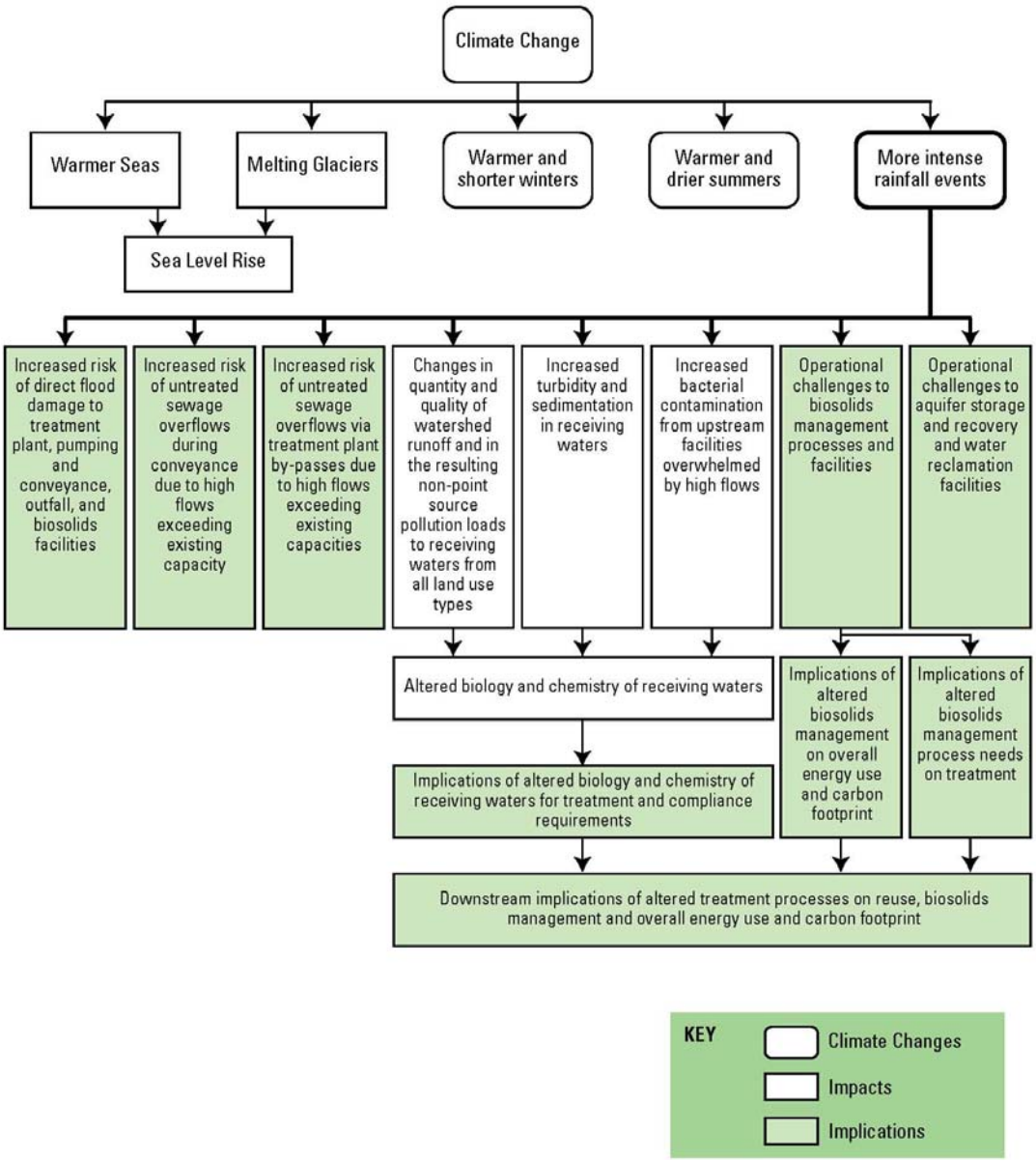


Figure 15.8.Impacts and implications of more intense rainfall events for wastewater agencies.
Source: Borrowed with permission from WERF, 2010.

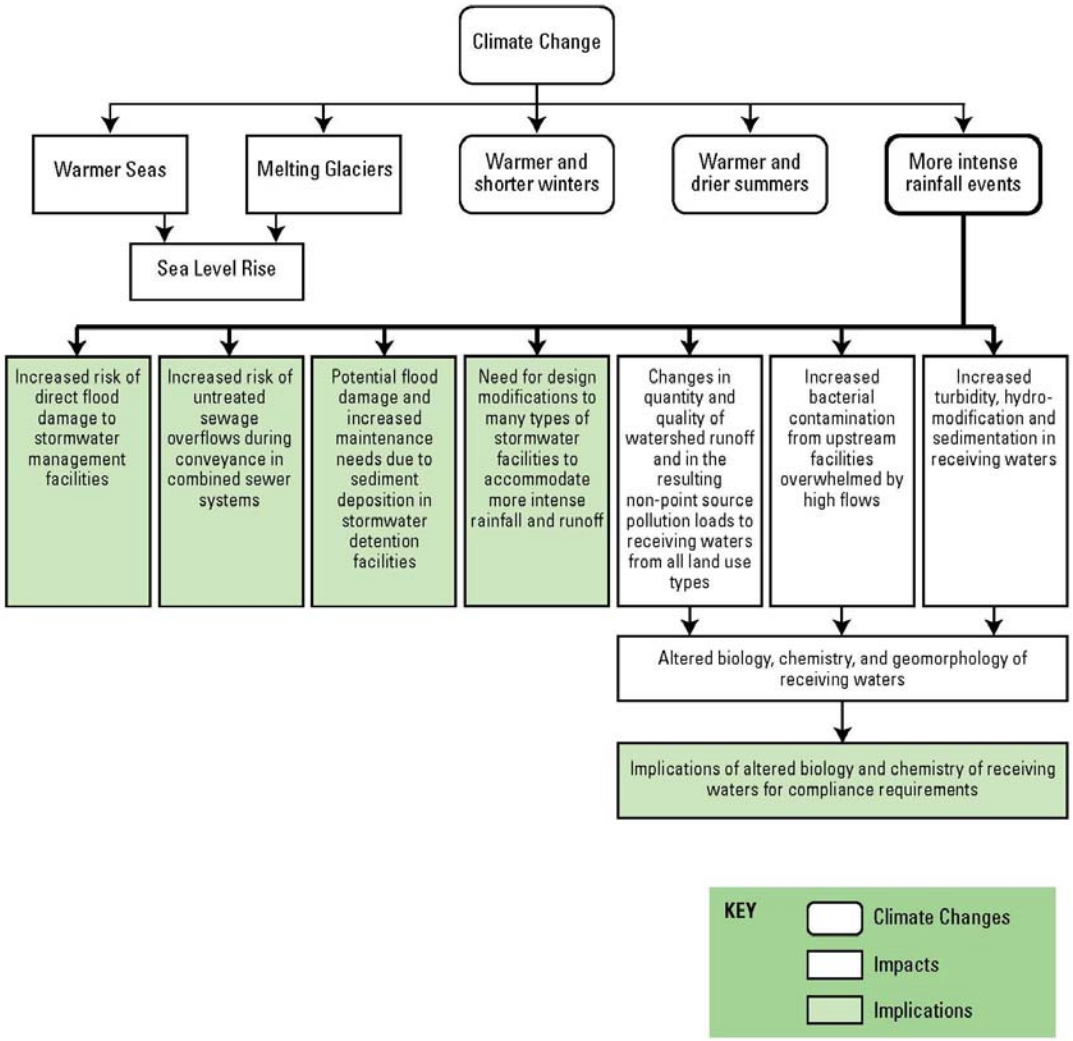


Figure 15.9.Impacts and implications of more intense rainfall events for stormwater agencies.
Source: Borrowed with permission from WERF, 2010.

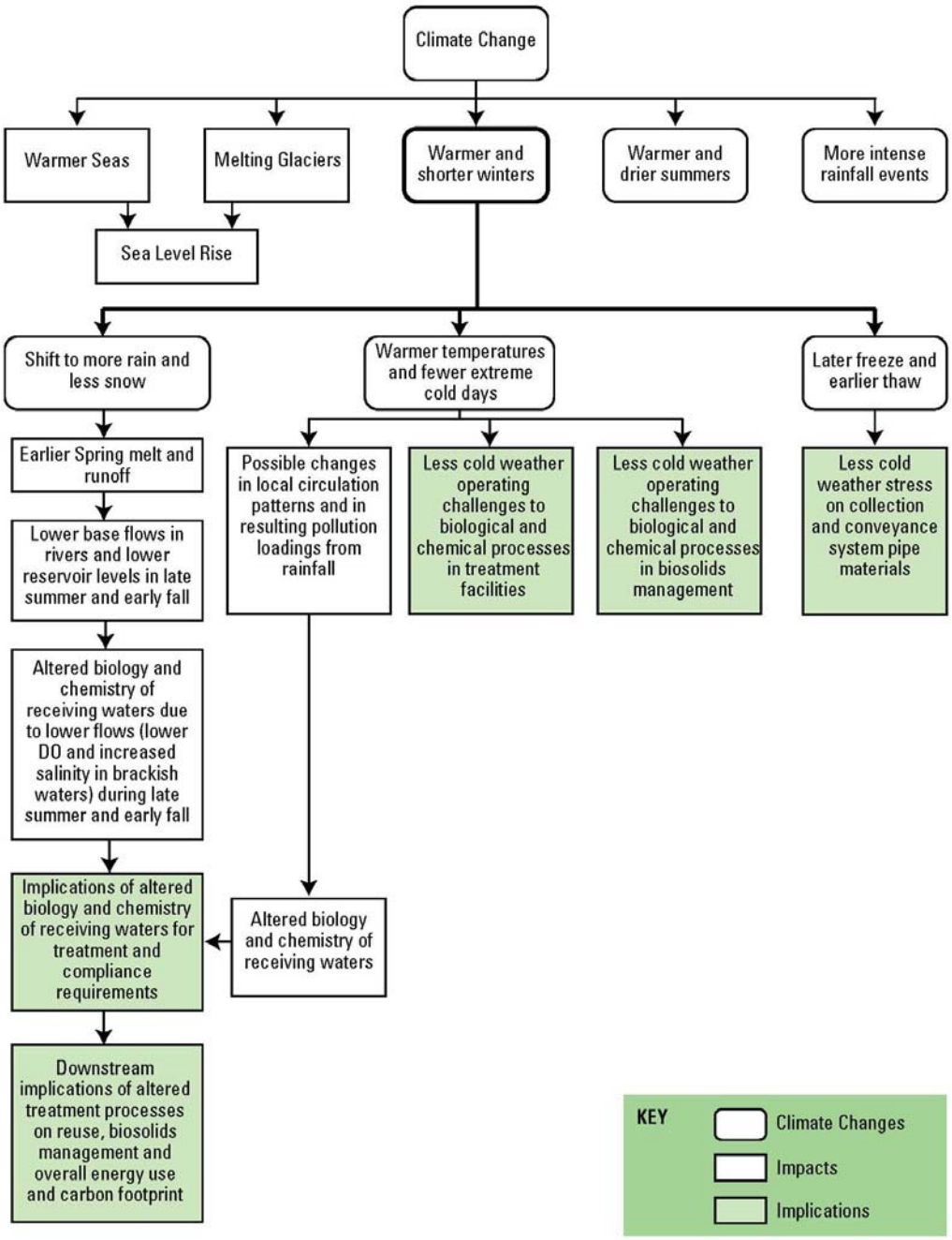


Figure 15.10.Impacts and implications of warmer and shorter winters for wastewater agencies.
Source: Borrowed with permission from WERF, 2010.

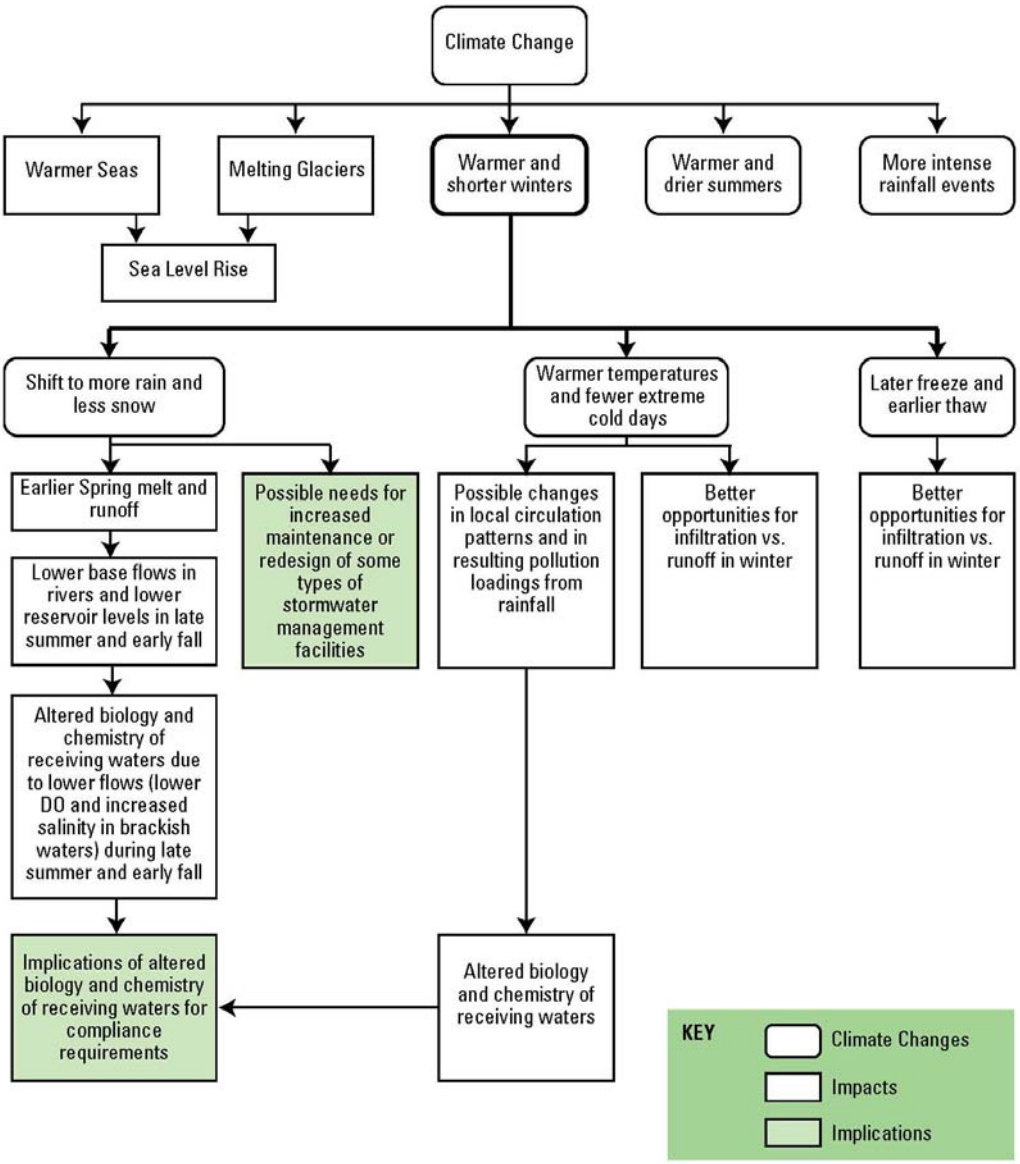


Figure 15.11.Impacts and implications of warmer and shorter winters for stormwater agencies.
Source: Borrowed with permission from WERF, 2010.

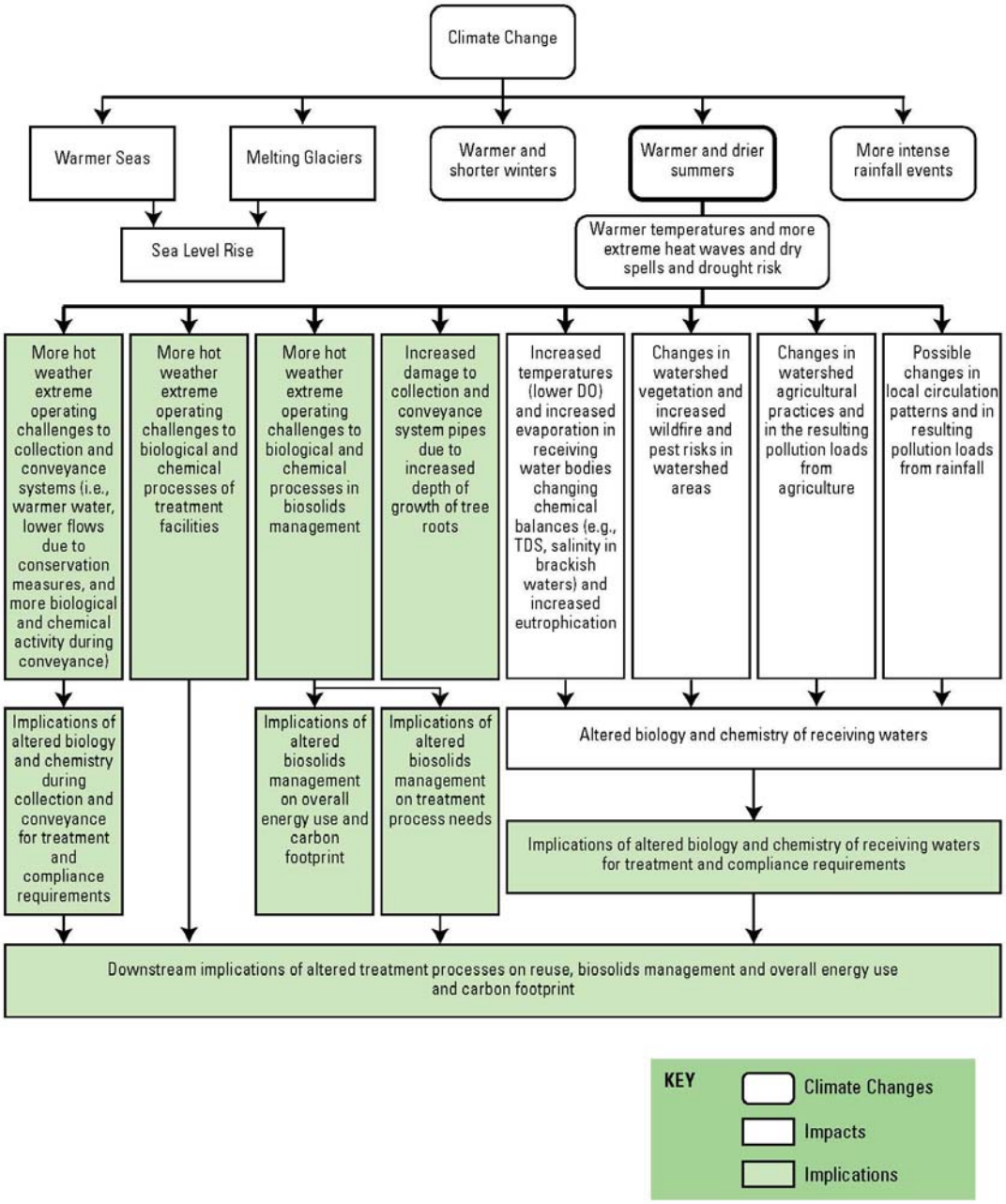


Figure 15.12.Impacts and implications of warmer and drier summers for wastewater agencies.
Source: Borrowed with permission from WERF, 2010.

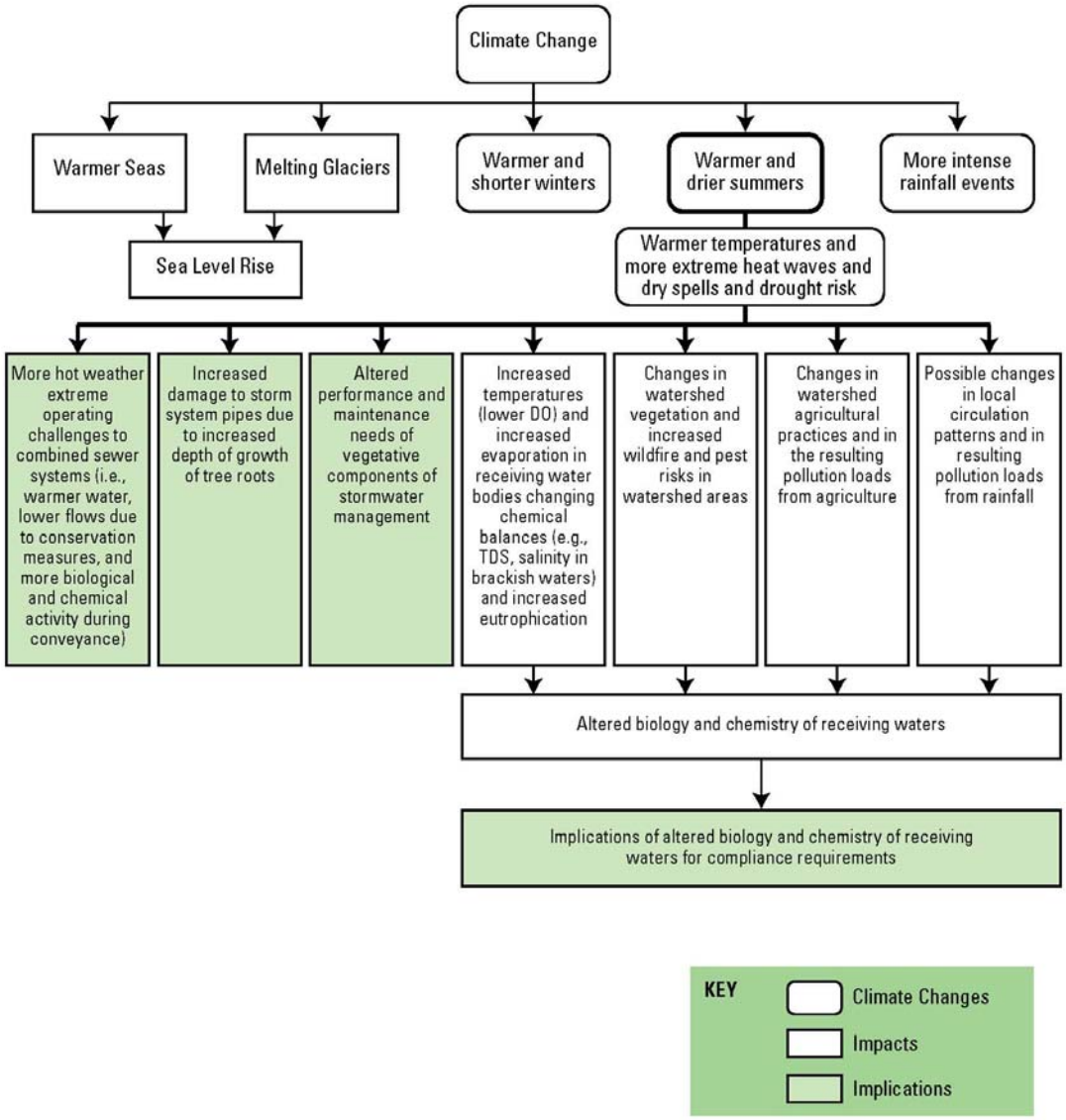


Figure 15.13.Impacts and implications of warmer and drier summers for stormwater agencies.
Source: Borrowed with permission from WERF, 2010.

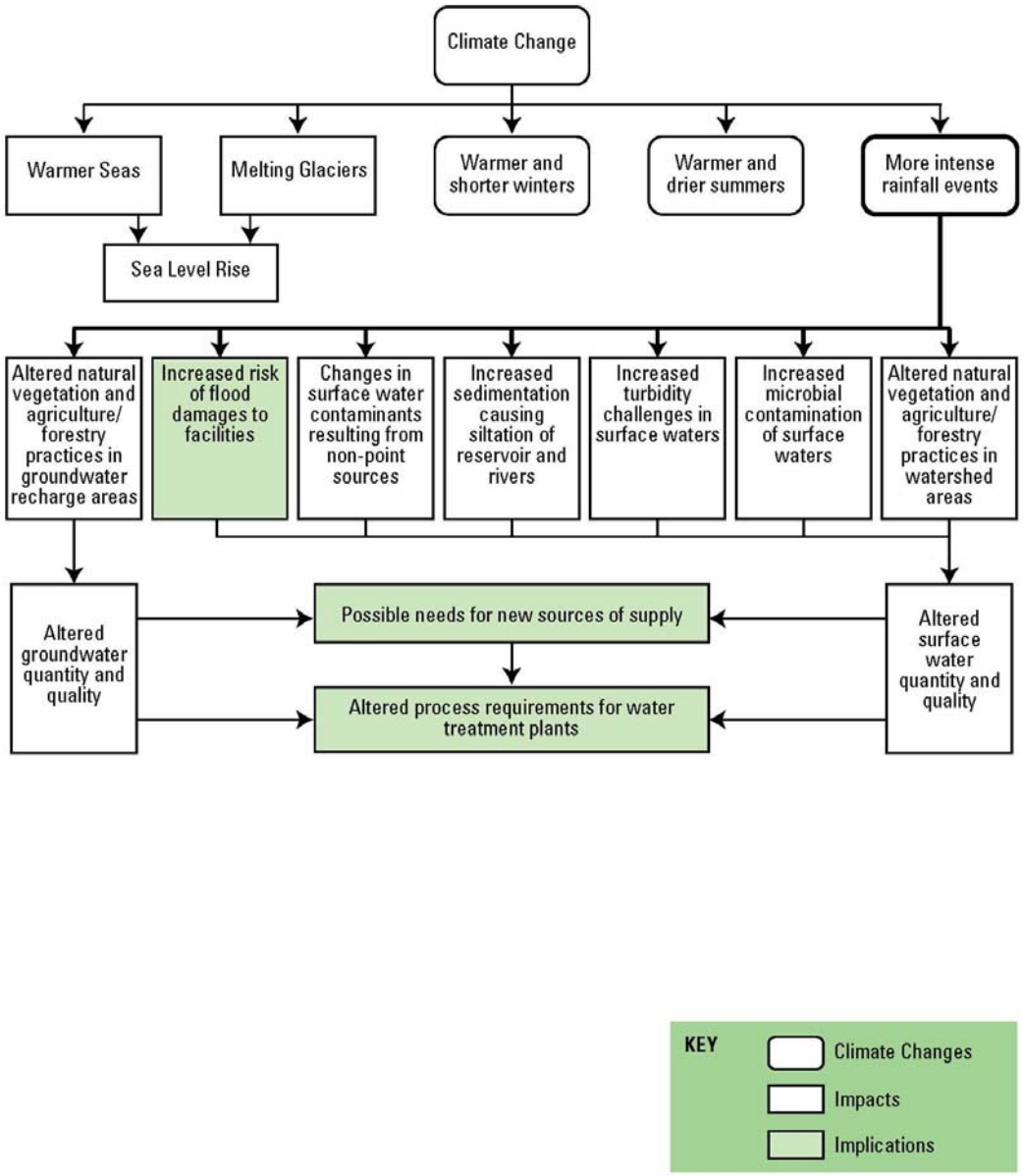


Figure 15.14. Impacts and implications of more intense rainfall events for water supply.
Source: Borrowed with permission from Cromwell et al., 2008.

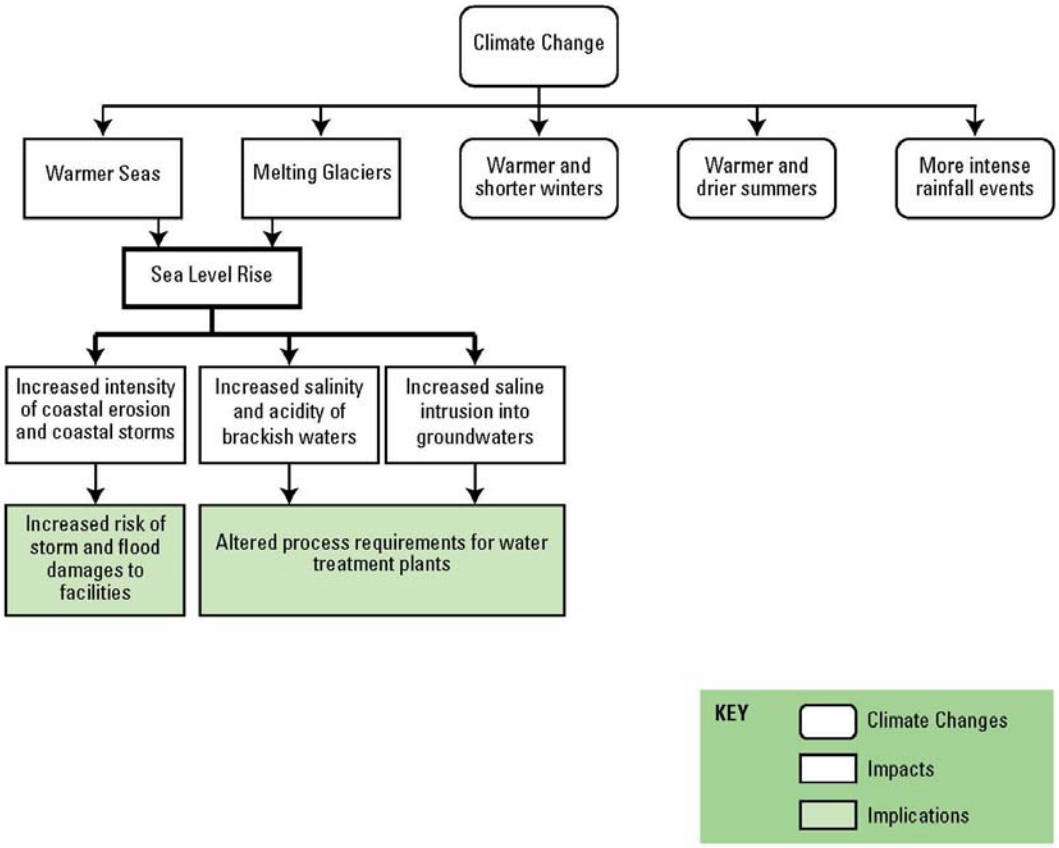


Figure 15.15. Impacts and implications of SLR for water supply.
Source: Borrowed with permission from Cromwell et al., 2008.

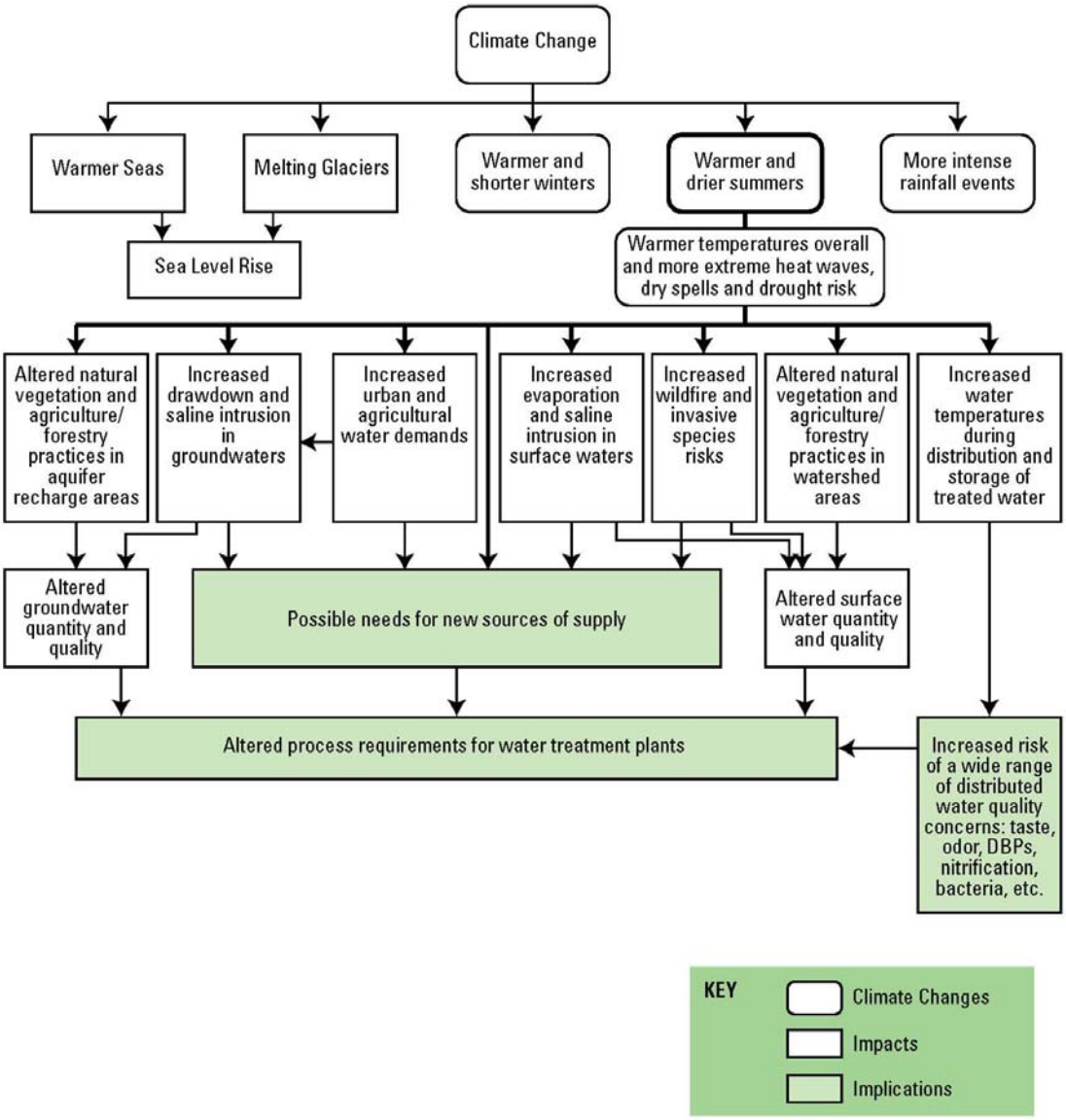


Figure 15.16. Impacts and implications of warmer and drier summers for water supply.
Source: Borrowed with permission from Cromwell et al., 2008.

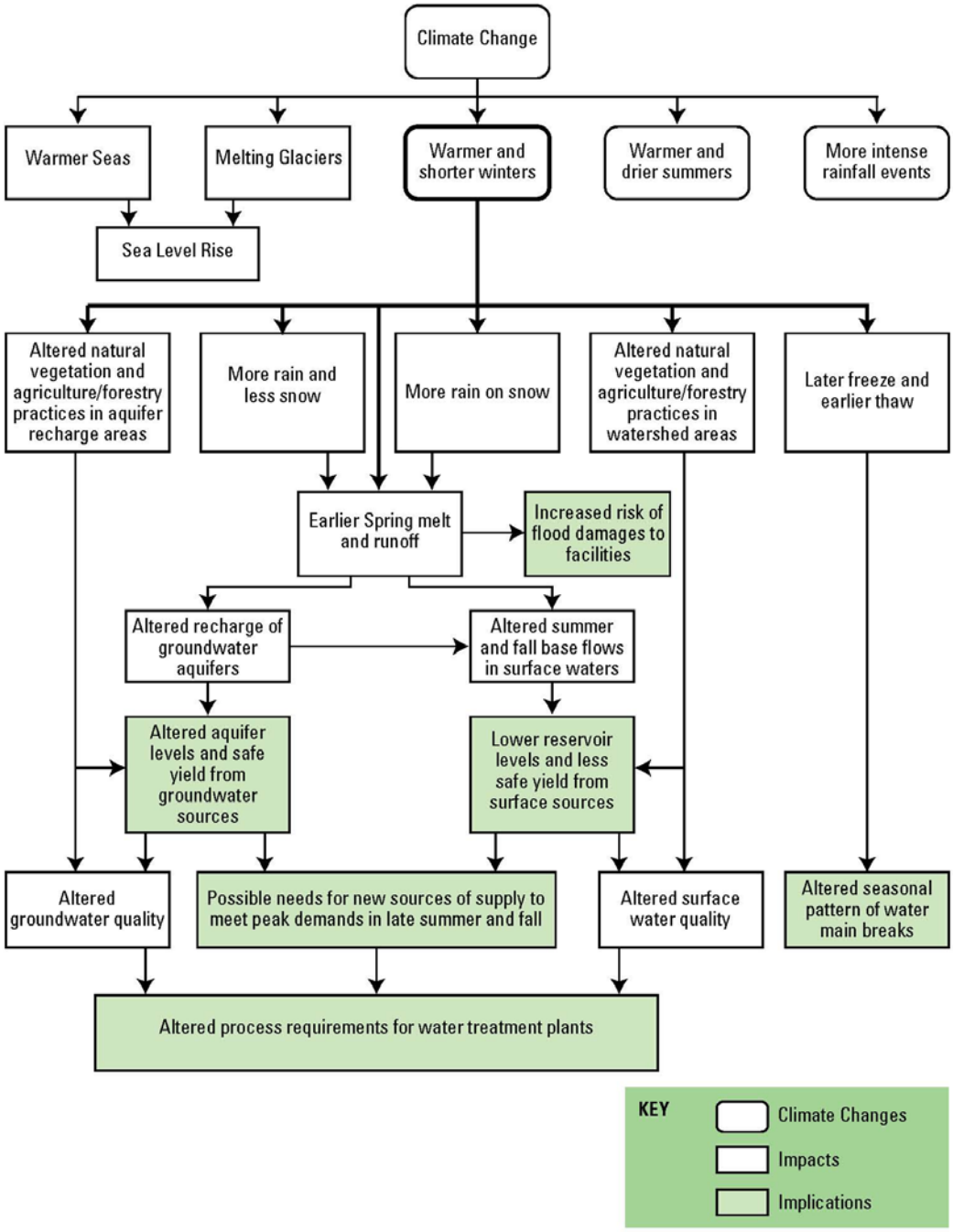


Figure 15.17. Impacts and implications of warmer and shorter winters for water supply.
Source: Borrowed with permission from Cromwell et al., 2008.

A:Warmer and drier summers

Altered groundwater quality and quantity

A1: Increased drawdown and saline intrusion in groundwaters

- Probability—Possible to likely
  - Consequence—Major to catastrophic (groundwater is sole source);possible need for new supply (consider reuse, a climate independent source)

A2: Altered process requirements for water treatmentplants

- Probability—Possible to likely
- Consequence—Insignificant to low, current treatment can handle projected changes

B: Warmer and shorter winters

More rain and less snow

B1: Water supply—Altered recharge of groundwater aquifers

- Probability—Almost certain
- Consequence—Major to catastrophic (groundwater is sole source);possible need for new supply(consider reuse, a climate independent source)

B2: Wastewater—Altered biology and chemistry of receiving waters

- Probability—Almost certain
- Consequence—low to minor as treatment can handle projected changes

C: More intense rainfall events

Altered groundwater quantity and quality

C1: Water supply—Altered natural vegetation in groundwater recharge areas

- Probability—Possible to likely
- Consequence—Major to catastrophic (groundwater is sole source); possible need for new supply(consider reuse, a climate independent source)

C2: Stormwater—Altered biology, chemistry and geomorphology of receiving waters

- Probability—Possible to likely
- Consequence—Low to minor as treatment can handle projected changes

Figure 15.18.Risks identified as possible because of climate change.

Chapter 16

Tools for Identifying Potential Climate Change Risks and Vulnerabilities

Chapter 2 in Part I illustrated the need to differentiatebetween potential climate changes and potential climate change impacts. This chapter is designed to help utility planners take their knowledge of potential impacts and quickly identify which of these impacts represent potential risks for their utility. The chapter provides a primer on "risk," and once the potential risks have been identified, a simple tool is provided for characterizing those risks.

16.1 An Overview of Risk Management

The term "risk management" has been defined and deployed in many settings. We adopt the general convention that originates with the National Research Council (NRC, 1983), which distinguishes *risk assessment,* identifying and attempting to estimate the size of a risk, from *risk management,* the decision-making steps of merging risk assessment information with other relevant factors to determine how to act in the face of the risk. In the climate change context, the risk assessment component corresponds to vulnerability assessment (i.e., aiming to understand and prioritize the risks that utilities face), and the risk management component refers to the process of planning and implementing adaptations (i.e., considering actions to reduce the probability and/or consequences of the risks).

To help forge a useful approach for W/WW utilities, we view the risk management framework as consisting of the following four steps, and will structure our approach accordingly:

1. *Risk identification*—recognizing and understanding *how climate is changing*, and may change further in future decades (generally on a global scale and with an annual/seasonal time step).
2. *Risk assessment*—identifying *how climate change will impact the environments (natural/social) within which water utilities operate* (e.g., less summer precipitation, reduced streamflows) fora utility-relevant geographic scale (e.g., watershed, service area) and time step (monthly, daily).
3. *Risk characterization*—building from the prior risk identification and assessment steps to form a *vulnerability assessmentofhow the projected potential changes in W/WW utility operating environments will pose risks to utilities* (i.e., raising the probabilities and/or consequences of adverse outcomes). The vulnerability assessment is based on a cross-cutting evaluation of
    a. Risks arising from *source to tap* (including watersheds, storage, treatment, distribution, and user demands), and
    b. Risks posed to *water quality, water quantity,* and *infrastructure* (including "secondary effect" risks such as population migration or pest infestation).

4. *Risk management*—identifying, evaluating, selecting, and implementing *adaptation strategies* (e.g., reuse) to increase resiliency and retain/add flexibility, using approaches such as adaptive management, "no regrets" (or "low regrets"), and "green infrastructure."

This four-step construct is very useful as a way of framing the risk management challenge, and for providing assessments of various tools, models, and approaches for examining each step. This perspective is summarized in Table 16.1.

Table 16.1. Steps in the Climate Change Risk Management Framework, and Associated Example Tools, Methods, and Uncertainties

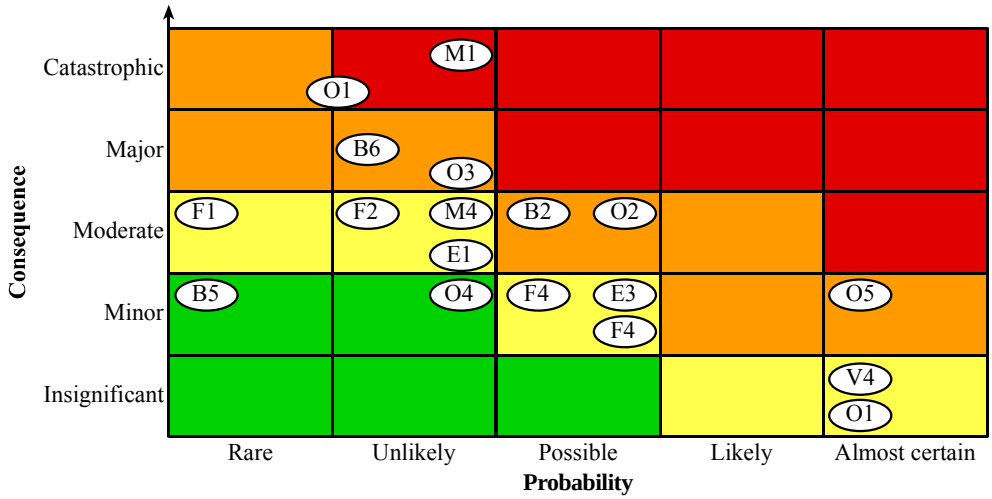
Risk Management Framework Step	Examples of Tools and Approaches	Key Issues and Uncertainties
	1. Risk Identification	
How will climate change at the global level? ▸ Temperature ▸ Precipitation	▸ Coupled models—GCMs ▸ Carbon dioxide equivalents (CO_2e) emissions scenarios	▸ 20+ GCMs have divergent predictions at global scale ▸ Emissions scenarios are widely divergent and uncertain
	22. Risk Assessment	
How will climate change impact environments (natural and social) in which water utilities operate? ▸ Streamflows ▸ Dry days between rainfall	▸ Downscaling to local and regional levels ▫ Regional climate models (RCMs) ▫ Statistical downscaling	▸ Adds uncertainty on top of GCMlevel ▸ Data generated not necessarily accurate or informative
	33. Risk Characterization	
How will climate change impacts on the operating environment pose risks for water utilities, source to tap? ▸ Water quantity ▸ Water quality ▸ Infrastructure	▸ Risk mapping ▸ Scenario analysis ▸ VSAT (hazards vulnerability) type model ▸ WEAP model	▸ Population migration and other secondary effects may significantly impact water utilities ▸ Changes in competing water demands (e.g., instream needs, agriculture) difficult to predict
	4. Risk Management	
What are the best options for adapting to potential climate change impacts? ▸ No/low-regret options ▸ Timing and phasing of responses	▸ Scenario planning ▸ Robust decision-making (RDM) ▸ TBL ▸ Regrets analysis ▸ Adaptive management ▸ Low-impact development	▸ Divergence in projected climate change impacts increases potential for mal-adaptation ▸ Challenge of preparing for both episodic acute event risks (e.g., severe storm) and chronic risks (temperature increase, SLR)

16.2 A Risk Characterization Tool

Once you have developed a list of potential risks, as described in Chapter 15, it is helpful to characterize each type of risk. This can be done fairly simply by placing each risk in a risk-mapping matrix and assigning a risk level specific to your utility. This approach is designed to help you characterize and prioritize risks (and/or help determine where you need to gather more information in order to assess/prioritize a risk).

Figure 16.1 shows an example of this simple yet powerful risk- profiling tool, in which various risks across utility business areas are profiled according to their likelihood (probability) and associated consequences. In this example, the risks are organized by internal functional area (e.g., operations, information technology) and external events (e.g., terrorism, natural disasters). A simpler, climate-oriented version of the risk-profiling matrix approach was provided in Figure 5.6.

The risk-profile approach in Figure 16.1 is useful in several ways. It is a visual aid for understanding how the risks a utility faces may vary along the probability and consequence dimensions. It also enables and encourages utility managers (and invited stakeholders) to determine what cells reflect extreme- versus high- or lower-risk rankings. Risk profiling in this manner encourages utilities to consider a broad range of risks, and enables them to begin to characterize them. It also allows practical judgment to enter the process (i.e., it is not simply a formulaic black box), as managers need to consider what each category of likelihood or consequence means. Not all risks can readily be assessed quantitatively in terms of probabilities and consequences, yet this framework enables a utility to attempt to portray these risks and develop an initial prioritization. It also enables us, and utilities, to consider how climate-change-related risks relate to other important risks utilities face.



Operational Risks
O1 Contaminated water supply
O2 Water asset failure
O3 Chlorine gas leak
O4 Incorrect asset design
O5 Unaccounted water loss

Event Risks
VI Threats to employees
V2 Vandalism
V3 Natural disaster
V4 Vehicle accidents
V5 Sabotage/terrorism

Market/Regulatory Risks
M1 City water system failure
M2 Poor contract management
M3 Unauthorized purchases
M4 Regulatory noncompliance

Business/Information System Risks
B1 Architecture capacity not sufficient
B2 Unauthorized access
B3 Inappropriate handling of media
B4 Critical information not recorded
B5 Lack of community consultation
B6 Key IT system failure

Financial Risks
F1 Liquidity, cash flow
F2 Credit rating downgraded
F4 Major customer bankrupt

Employee Relations Risks
E1 Noncompliance with OSHA
E2 Loss of key personnel
E3 Inadequate training

Risk ratings:
Extreme
High
Moderate
Low

Figure 16.1. Utility risk profile: Characterizing and ranking various utility risks.

Chapter 17

Decision Support Tools

Whether you use complex computer models or a bottom-up identification analysis, at best the information you have gathered about potential climate change impacts on your utility is vague, uncertain, and based on best guesses. And although you have ideas on how to adapt, you may have no idea if these adaptive strategies make sense for your utility financially or otherwise. All this uncertainty makes integrating climate change information into planning one of the most intricate steps utilities will face in the climate change adaptation process.

Before you worry too much, though, remember thatyou have been planning underuncertainty for years, including population growth, changes in consumer behavior, technological advances, and shifting regulatory requirements. All of these changes require planning underuncertainty. In some cases you dealt with these uncertainties by applying probabilities to them. In other cases you identified the options that ensured that you made no major long-term mistakes. In others you looked at what scenarios provided the best overall solutions to all your unknowns—robust decision-making (RDM).In others you used a benefit–cost analysis to see if the decision made sense.

Each of these approaches to decision-making under uncertainty may be regarded as applying a DST or a decision support planning model (DSPM). In this section we provide a brief overview of these tools and the pros and cons of each in helping you sort out how you make decisions when faced with uncertainty.

As you read through the DST descriptions, remember that

- None of these approaches isa sure-fire way to crank out the "right decision." Rather, they are tools designed to help organize and analyze the information you derived earlier in a format that will help you understand the implications of your various planning options.
- If you have bad information, a good DST will not make it better. It will only allow you to format and analyze that bad information (i.e., garbage in, garbage out).
- Many DST techniques require you to gather additional data—including probabilities or likelihood. If you donot have thesedata or you have hired an expert who doesnot have the data, you are likely to make uncertain information more uncertain.
- In addition, make sure the DST you choose is designed to answer your question. Many DSTs are designed to provide a least-cost solution. If your question is, "How do I make sure I don't burn any bridges I may need down the line?" then a least-cost DST is not a useful tool.
- When selecting a DST, choose one that will help you communicate. It is likely that you will need to pass on the information you have gathered along the way to other members of your utility (e.g., other planners, managers, the Board, customers, regulators, associates in other utilities). A DST should help you pass on the information in a clear, concise, easy-to-understand way that says,"Let's do this." If the DST you apply is presented as a black box, then you will not be able to convince others that its results are valid and useful.

- This is a good time to gather your collaborators:the internal team of engineers, operations officers, planners, and managers who provided information along the way and/or will ultimately make the decision. Working together before any decisions are made—explaining the data and data limitations, options, etc., and deciding together what questions you need answered—will go a long way toward reaching consensus on final decisions.
- Finally, before you start any planning process, make sure you have an explicit understanding of your level of risk acceptance for particular resources and/or outcomes. For example, zero tolerance for water use restrictions might require very expensive infrastructure or economically inefficient operations. On the other hand, a willingness to accept some water use restrictions over specified time horizons may decrease costs significantly. There is no right or wrong answer here, but considering this issue explicitly can assist in better decisionmaking.

17.1 Some Types of Decision Support Tools

There are many DSTs out there. However, because we cannot look at them all, the following have been selected as being the most helpful:

1. Incremental decisions/adaptive management
2. Portfolio approach
3. Integrating systems
4. No regrets
5. Benefit–cost analysis
6. Triple bottom line (TBL) assessment
7. Classic decision analysis
8. Traditional scenario planning
9. RDM

The first four DSTs were also discussed in the section on adaptive strategies. They are included again here to remind you that although they are adaptive strategies, they can also be used as DSTs.

Incremental decisions/adaptive management supports the idea that, in many cases, there is no need to solve a problem all at once. By designing decisions to be incremental in nature, you hedge against uncertainty by allowing the decision to be revisited for course corrections as events unfold and climate science improves. This kind of decisionmaking, often referred to as adaptive management, also includes active monitoring, upfront investments to enable inexpensive modifications to infrastructure, and mandatory reassessments of the policy.

Although closely related to incremental decisions, the concept of flexibility goes a bit further in the portfolio approach. When you are faced with an array of potential policy alternatives, it often makes sense to pick the most flexible alternative. For example, diversifying a utility's water supply portfolio by adding reuse water or groundwater to a predominantly surface supply system inherently increases the flexibility of that system in a way that simply expanding an existing surface water supply may not.

Another approach to increasing flexibility for currently isolated water supply or wastewater systems is integrating systems. Integrated systems inherently increase flexibility in comparison to isolated systems. For example, a utility can withstand a supply shortfall in one basin by integrating neighboring water supply systems, thus allowing water resources to move between the two basins.

In many cases, multiple policy alternatives exist to address climate change. Your job is to make sure that whatever you decide, it is likely to result in no regrets. Most adaptations to climate change serve other important economic, environmental, or social objectives. When possible, choose adaptations that make sense for multiple reasons so that the benefits are not dependent on uncertain climate projections. In this way, you improve confidence that the decision is a good one, regardless of the future climate. Note that not all climate impacts can make use of no-regrets adaptation strategies. For example, elevating a WWTP along the coast in anticipation of SLR may require incremental cost increases to the infrastructure project, but will avoid costly retrofits should SLR occur. But if SLR does not occur, you may regret having spent a lot of money on elevating the WWTP. Also note that even this option may provide no-regrets benefits because ofprotection provided against coastal storm surges (whether or not SLR occurs).

The main difference amongDSTs described is how they handle uncertainty. Classic decision analysis assigns probabilities to uncertainties, traditional scenario planning develops equally likely scenarios, RDM combines different variations of these two approaches, and the TBL allows you to solve for more than one objective (and can be used within any of the other DSTs).

A benefit–costanalysis allows you to answer themost basic of questions: am I better off doing this than not doing this? All decisions have benefits and costs. Treating them explicitly and looking at the trade-offs among policy alternatives can lead to more clarity in the decision-making process and ensure that all necessary information is brought to bear before a course of action is decided on. In completing a benefit–cost analysis, it is important to note that not all benefits are financial. Benefits can also include providing flexibility (i.e., not burning any bridges) and protecting nonmarket resources (e.g., wildlife, water quality changes that are not easily quantifiable). Consider a benefit–cost analysis as you would a list of pros and cons. On one side are all the benefits—all the good things that would result even if you donot have a dollar figure for them. On the other side are all the things it will take to make it happen. Dollars are certainly one thing to include, but theymight also cost you a trade-off—if I do this, I cannot do that. By comparing your lists of options, you can get a good feel for the trade-offs between options, as well as a financial comparison of the benefits and costs of each option over time. You donot need to develop probabilities for a benefit–cost analysis (although a probabilistic benefit–cost analysis is sometimes a useful tool, especially where uncertainties are prominent).

A TBL assessment is a form of benefit–cost analysis in whichthe outcomes are considered along three dimensions: financial outcomes (i.e., the traditional bottom line generated by accountants, focusing on cash flows in and out of the utility), social impacts (a second bottom line, including issues such as supply reliability, affordability, and public health), and environmental impacts (the third bottom line, including elements such as carbon footprint and water quality).

Like the other DSTs described, a TBL assessment will not tell you what specific decision to make. Instead, it will provide information that will help you and your utility better understand

the implications of the options you are considering. This information will be in the form of the benefits and costs of your options, including financial, social, and environmental outcomes.

A TBL analysis can be done independent of the other DST options. Alternatively, a TBL approach can be done as part of another DST. For example, a scenario analysis can be developed in which the outcomes under each scenario are cast within a TBL framework. This tells you about the benefits and costs that are associated with the choices that you might consider under the different possible future scenarios.

Classic decision analysis is probability-based. It provides support for decisionmakers by systematically cataloging information and mathematically evaluating and ranking decision alternatives against multiple, potentially conflicting decision objectives. Classic decision analysis illustrates the process with a decision tree or influence diagram and handles uncertainty through the use of probabilities. Fundamentally, classic decision analysis is used to find a preferred plan with the best value, which often is the lowest expected cost (Means et al., 2010).

A key data need for classic decision analysis is the probabilitiesof future events occurring. When climate change uncertainty is considered, probabilities can be difficult to assign to future conditions, arbitrary, and hard to defend. In situations in which probabilities cannot be scientifically or mathematically determined, expert judgment can be used to assign probabilities (Means et al., 2010). Water utilities that are deciding whether to use classic decision analysis for climate change planning must carefully consider their willingness, and ability, to assign probabilities to climate model projections.

Traditional scenario planning is, as its name suggests, scenario-based. The main objective of traditional scenario planning is to develop a plan that best prepares the water utility for a plausible range of uncertain circumstances. Scenarios are developed through the identification of critical uncertainties and driving forces. These driving forces might involve uncertainty surrounding climate, water quantity, water quality, demand, social and regulatory change, technology, economics, or other elements (Means et al., 2010).

The goal is to develop a range of future conditions that go beyond extrapolation of current trends and represent surprising but plausible conditions. Typically, scenarios are treated as equally likely to occur, rather than assigned probabilities, as in classic decision analysis. Implications and future needs of each scenario are identified and adaptation strategies are developed to meet the needs of each scenario. Ideal adaptation strategies have near-term actions that are common to all or most scenarios. These are sometimes called no-regrets or low-regrets strategies. Signposts can be established to monitor the development of the scenarios and determine when adaptation measures are no longer common to all or most scenarios.

Scenario planning is fairly easy to understand and is familiar to many utilities. Although it engages stakeholders, those with difficulty contemplating multiple alternative futures and applying current strategies to those futures can become frustrated with the process. The resource requirements for scenario planning can be minimal or extensive, depending on the level of detail desired in the analysis (e.g., number of scenarios, number of stakeholders, detail of the strategies). Outside experts are not essential to the process but can facilitate the development and evaluation of scenarios by challenging conventional wisdom and offering additional perspectives.

The requirement to characterize plausible future conditions using a small number of scenarios can limit the ability of traditional scenario planning to address future uncertainty. Scenario planning also does not always simplify decisionmaking, as each scenario may suggest disparate strategies and the methods do not guide the reconciliation of those strategies. A benefit of traditional scenario planning is that those involved in the planning process do not need to agree on a single future when developing the plan (Means et al., 2010).

RDM is a framework that combines features of classic decision analysis and traditional scenario planning. The approach provides a systematic way todevelop a water management strategy to best adapt to a wide range of plausible future conditions. RDM uses existing or modified water management models to evaluate candidate strategies against large sets of quantitative scenarios that reflect future uncertainty. Sophisticated techniques are then used to identify major vulnerabilities within these strategies. Analysts, stakeholders, and decisionmakers study these vulnerabilities to develop hedging options and to design alternative strategies. Successive iterations through these steps reveal increasingly robust strategies.

RDM provides decisionmakers and stakeholders with a small set of robust strategies to choose from and information about what assumptions must be met for each choice to be successful. For many agencies, a completely robust strategy will not be identifiable. RDM thus presents the key trade-offs of one candidate strategy versus another. In addition, consequences that particular future conditions might have for each strategy are identified. This enables decisionmakers to determine which risks to address in their long-term plans.

RDM is particularly useful when agencies want to examine uncertainties that cannot easily be assigned probabilities. Also, it does not require agreement by decisionmakers, experts, or stakeholders on the likelihood of different future conditions occurring. The method is most useful when there are many decision alternatives and a detailed analysis of every possible variant is not possible. Expertise at this point is concentrated among a small group of practitioners and requires fairly sophisticated computing and analytic capabilities, although several applications with different water agencies are currently underway (Means et al., 2010).

During the Inland Empire modeling project discussed in Chapter 6, RAND used a DSPM to identify how well the Inland Empire Planning Scenarios meet the agency goals, given what had been concluded about climate change impacts from modeling steps 1–3. In step 4, RAND used three DSTs—traditional, scenario, and RDM. A brief description of how this was done and the outputs provided isillustrated in Figure 17.1.

In Chapter 6, an example from the Inland Empire illustrated three uses of computer modeling to help plan for climate change—GCMs, downscaling, and hydrologic modeling. In this section we look at how the information gained from these steps was then input into a fourth step—a DSPM. The DSPM looks at how well identified adaptation strategies meet agency goals given projected climate impacts.

RAND identified potential adaptations based on the planning scenarios developed by the Inland Empire in the 2005 IEUA Regional Urban Water Plan (IEUA, 2005). The ranges of planning scenarios are the planning options currently on the table for the Inland Empire and include a significant investment in reuse, recycling, and replenishment.

RAND modeled a traditional scenario analysis, a probability-weighted scenario, and a RDM analysis. Model outputs identified changes in demand, available supply, annual shortages, financial effects of shortages, and the cost of provisioning supply. These outcomes were then summarized as the present value of costs and the financial effects of shortages.

The traditional scenario analysis demonstrated that all of the planning scenarios perform well, even if the Inland Empire does not meet recycling and replenishment goals, if the future climate is benign, that is, wetter than historic conditions. If the future climate is adverse, that is, drier and warmer than historic conditions, IEUA needs to meet recycling and replenishment goals, as well as investing in more efficiency, and possibly allowing more recycled groundwater replenishment to ensure sufficient supply to meet demand.

The probability-weighted scenarios suggest that, assuming that the probability estimates are spoton, the chance of a shortage over the next 25 years is less than 7% for any of the plans outlined in the Inland Empire RUWMP. Probabilistic scenarios can provide a concise ranking of the desirability of alternative IEUA plans but can lead to errors of omission in planning by downplaying the potential importance of possible futures that deviate from the likeliest conditions. Further, effective use of probabilistic scenarios may require a wide range of stakeholders to agree on the validity of the distributions used in the analysis.

RAND also used the model to ask a variety of questions designed to assist planners, including the following:

- Assessing how effectively IEUA planning scenarios keep the need for increasing purchases of imported waters to a minimum, both if there are no changes in the climate and ifthe climate becomeswetter
- Evaluation of hundreds of scenarios that explored assumptions about climate change, groundwater hydrology, urban growth, and similar conditions
- Identifying, as a “statistical-discovery” analysis, the three conditions that need to exist simultaneously for IEUA’s plan to lead to large future costs: (1) large declines in precipitation, (2) large changes in import availability and cost, and (3) small or large reductions in natural percolation in the Chino Basin
- Exploring howIEUA could mitigate these vulnerabilities—in particular, which actions to take now and which it can defer untillater

Figure 17.1.An example of a DSPM from the Inland Empire.

17.2 What Should I Consider When Selecting a Decision Support Tool?

Several DSTs are available to assist water utilities in planning for climate change. It is clear, however, that there is not a one-size-fits-all method and that every process must be tailored to the utility’s needs and capabilities. For utilities that are not interested in methods requiring sophisticated computing or modeling, scenario planning is fairly intuitive and can be accomplished with minimal external resources. Even without going through the traditional

development process, useful climate change scenarios can be derived by a review of available climate model projections for the region and selection of plausible ranges (i.e., a 15% increase or decrease in volume or storm frequency) without the needto use or manipulate climate data in models or assign probabilities.

On the other hand, utilities looking for, and confident in, a probabilistic assessment may look to classic decision analysis. The increasing computational power ofclassic decision analysis allows the consideration of a broader range of adaptation strategies. The general lack of analysis or accepted practice for assigning probabilities to climate model projections should be recognized. Water utilities that decide to use classic decision analysis must carefully consider their willingness to assign probabilities to climate model projections. Utilities that want to invest more resources and rigor in climate change adaptation strategy development may consider more advanced computational methods or hybrid methods such as RDM, real options, or portfolio planning.

This chapter is largely based on a paper compiled for the Water Utility Climate Alliance (WUCA; Means et al., 2010). We recommend that you take a look at that report for a more detailed description of several of these important decision-support processes.

Remember that the first step is to identify the question you are trying to answer and then select a DST that can help you with that question. Remember also that the DST should provide you with an excellent format for communicating the answer to others.

Chapter 18

A Summary of Sea Level Rise Projections and Uncertainties

Projections of SLR are very important for Miami and other coastal locations. There currently is a lot of controversy concerning projections of SLR. As we discuss later, IPCC's latest projections of SLR are relatively low. These projections have been criticized as being too optimistic (i.e., too low; Oppenheimer et al., 2007). In contrast, the Miami-Dade County Climate Change Advisory Task Force, Science and Technology Committee, concluded that many scientists see "a likely SLR of *at least*1.5 feet in the coming 50 years and a total of *at least*3–5 feet by the end of the century…"(Science and Technology Committee, 2008; emphasis added).

This note briefly reviews the latest projections of increases in global (eustatic) sea levels over the rest of this century, and then discusses what this may mean for Miami.

18.1 Projections of Global Sea Levels

Global sea levels have been increasing because of higher temperatures, which cause oceans to expand. In addition, higher temperatures cause melting of glaciers and major ice sheets (such as Greenland), which further raise sea levels. Sea levels rose about 1.5–2 mm per year over the 20th century, but since the early 1990s have been rising 3 mm per year (see Figure 18.1).

One thing is clear: higher global average temperatures will in all likelihood result in more SLR. Indeed, all major assessments of SLR conducted since 1990 project further increases in sea level this century. What differs—and what there does not appear to be a consensus about—is the magnitude of future SLR.

Projections of future SLR vary widely. In its latest assessment, the IPCC projected that sea level will rise 0.2 to 0.6 m (0.5 to 2 ft) by 2100 relative to 1990 (*Climate Change 2007*, 2007). Since its first report in 1990, the IPCC has projected that sea level will rise in the 21st century. What has differed from report to report is the amount of projected SLR. Table 18.1 displays SLR projections from the four published IPCC assessments. Although the projections differ and appear to be decreasing over time, the IPCC has consistently projected an increase in sea level.

The latest projections from the IPCC shown in Table 18.1 do not account for potentially significant melting of major ice sheets in Greenland and West Antarctica. Each ice sheet contains enough water to raise sea levels 7 m (23 ft), but, because of the immense mounts of water involved, it would take centuries to millennia for that amount of SLR to happen even with destabilizationof these ice sheets. The 2007 IPCC report concluded that accelerated melting of major ice sheets might increase sea levels up to 0.25 m (about 10 inches) more than the projections given in the 2007 report (see Table 18.1). This would result in an IPCC-adjusted projection of total SLR by 2100 of between 0.45 and 0.85 m (1.3–2.8 ft), relative to sea levels in 2000.

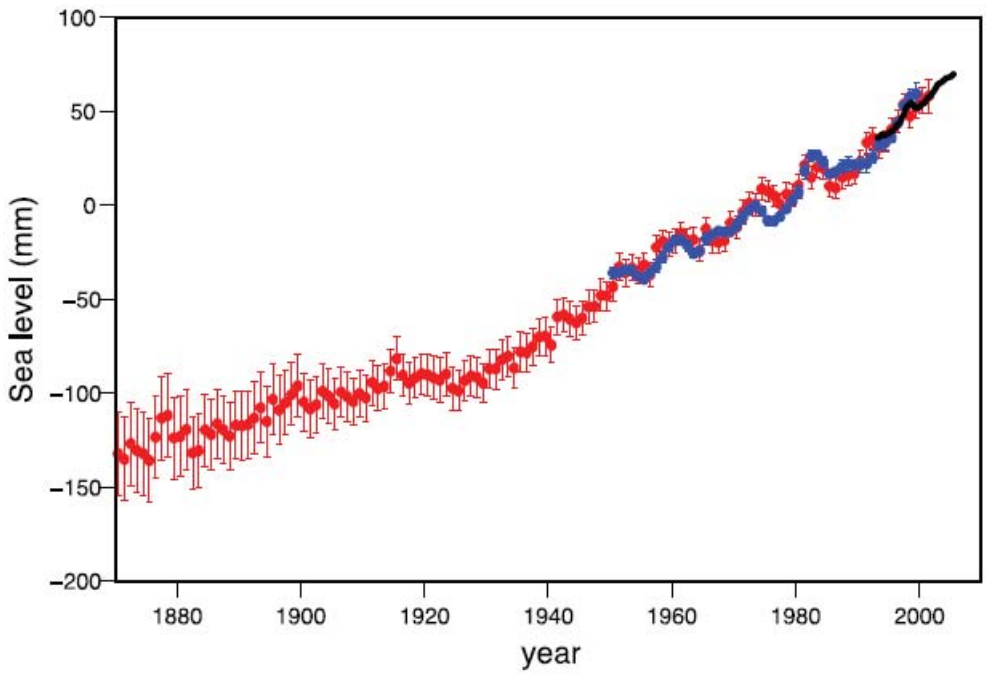


Figure 18.1.Observed changes in eustatic sea level.

Note: The red curve shows reconstructed SLR from 1870 to the present; the blue curve is based on coastal tide gauge measurements since 1950; and the black curve is based on satellite data. The error bars show 90% confidence intervals.

*Source:*Bindoff et al., 2007; Figure 5.13, p. 410.

The IPCC report does not account for the potential for rapid changes in the major ice sheets (Oppenheimer et al., 2007; Vermeer and Rahmstorf, 2009). Several studies published after the IPCC report have attempted to account for the potential for more rapid ice sheet melting and have estimated that sea level could rise 1.5 to 2 m (5–6.6 ft) by 2100 (Rahmstorf, 2006; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009). It appears that accounting for the more rapid ice sheet melting can add up to another meter (3.3ft) of SLR by 2100. However, Pfeffer et al. (2008) concluded that the most likely amount of SLR by 2100 is 0.8 m (2.6 ft).[9] This implies that although a 2m SLR is possible, it is not likely. Indeed, Pfeffer et al. (2008) stated that "increases in excess of 2 m [by 2100] are physically untenable" (p.1340). In other words, the latest scientific judgment is that SLR will not exceed 2 m by 2100.

18.2 Relative (Location-Specific) Sea Level Rise

There are three important components of*relative* SLR at any given coastal location (i.e., how much SLR is observed at a given location). The first is average global (eustatic) sea level. This change in the eustatic sea level resulting from climate change is what often receives the most attention.

[9] Using the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) 5.3 (Wigley, 2008), we estimated that a scenario yielding a 0.8m (2.6ft) SLR by 2100 would have 25.7 cm (~10 in.) of SLR by 2050 relative to 2000.

Table 18.1. IPCC Projections of SLR by 2100 (m)

IPCC Report	Low Projection	Best Estimate	High Projection
1990 report (*Climate Change*, 1990)	0.3	0.65	1.1
1995 report (*Climate Change 1995,* 1996)	0.15	0.5	0.97
2001 report (*Climate Change 2001*, 2001)	0.09	0.48	0.88
2007 report[a](*Climate Change 2007*, 2007)	0.18	N/A	0.59

Note: No "best" or middle estimate was given in the 2007 IPCC report, although the range of increase in sea level under the A1B emissions scenario, which is approximately in the middle of the emissions scenarios used by the IPCC, is 0.21 to 0.48 m.

The second component is regional variation in global SLR. SLR is not uniform, as there are important regional differences in projections. (Indeed, current sea levels around the world are not uniform.) Differences in ocean temperature, atmospheric pressure, salinity, and changes in ocean circulation result in differing changes in sea level ona subcontinental scale. For example, the IPCC reports that SLR in the northeastern United States may be about 0.1 m (3 in.) higher than in the southeastern United States by the end of the century**.** These differences between regions of the world can be several tenths of a meter (half a foot or more) by 2100 (Meehl et al., 2007b; see also Bamber et al., 2009).

The third reason that relative SLR will differ at specific coastal locations is that coastal lands may berising or sinking (uplift or subsidence). The weight of the glaciers that covered much of the Northern Hemisphere tens of thousands of years ago lowered the land beneath them. As the glaciers have retreated, the land has been rising (uplifting). This is particularly the case in northern areas. Many other coastal areas are sinking (subsiding) because of damming of rivers, which provides sediments to deltas such as the Mississippi Delta; the pumping of groundwater;and the decomposition of wetlands and other organic matter. Also, shifts in the Earth's tectonic plates (plate tectonics) can cause uplift or subsidence in coastal areas. Parts of Louisiana, for example, are subsiding at a rate of almost 1 m (3 ft) per century. On the other hand, some coastal areas of the United States are rising (uplift), making realized sea level change less than the global average.

18.3 Relative Sea Level Rise—Miami-Dade

To account for regional variations in global SLR in Miami, we calculated the average regional variation in SLR near Miami from the eustatic rate over six GCMs from the IPCC. Output from the IPCC models is expressed as scalars to the eustatic rate at 0.5 × 0.5° resolution. Gridded values were obtained using SimCLIM software (CLIMsystems, 2010) and incorporated into our geographic information system (GIS) to derive an average scalar of 0.94 of the eustatic SLR for the GCM cell thatincludes Miami. (This means that relative SLR near Miami is 6% lower than global average SLR.)

To account for local crustal movement (due to subsidence from groundwater withdrawals, resource extraction, organic matter decomposition, etc.), we obtained tide gauge data for Miami from the NOAA (2008). As the tide gauge average includes a climate and anonclimate component, we removed the climate component using the current eustatic rate (1.8 mm/yr) from the IPCC (*Climate Change 2007*, 2007) adjusted by the regional scalar. We then

multiplied the annual subsidence rate by the respective number of years to derive the total subsidence for 2060 and 2100.

We used MAGICC, v. 5.3 (Wigley, 2008), to derive the eustatic SLR for both time periods and for each emissions scenario. Parameters for each emissions scenario were set as follows:

- B1—Sensitivity of 1.5 °C, low ice melt
- A1B—Sensitivity of 3.0 °C, mid ice melt
- A1FI—Sensitivity of 6.0 °C, high ice melt

Note that the ice melt in MAGICC adds up to about 0.4 m (1.3 ft) to SLR. However, the SLR impacts from the ice melt scenarios in MAGICC are not as large as more recent studies suggest. The net result is that the MAGICC result of a total SLR of less than 1 m by 2100 is well below the high-end estimate of up to 2 m of SLR from studies that include more rapid glaciation, such as Pfeffer et al. (2008) and Vermeer and Rahmstorf (2009).

The high-emissions scenario (A1FI from the IPCC Special Report on Emissions Scenarios [SRES]; Nakićenovic et al., 2000) assumes very high rates of growth in global income, moderate population growth, and very high fossil fuel use. The middle scenario (A1B) has the same economic and population assumptions as the A1FI scenario, but assumes more use of low-carbon-emitting power sources and clean technologies. Finally, the low-emissions scenario (B1) has the same population growth as the other two, but assumes a more service-oriented economy and even greater use of low-carbon-emitting power sources and clean technologies. We then scaled the eustatic rates by the regional scalar and added the total subsidence values calculated (results are shown in Table 18.2). Note that the estimates in Table 18.2 do not incorporate rapid deglaciation of major ice sheets. A rapid deglaciation could add several more meters of SLR this century, leading to SLR of over 1.8 m (6 ft) by 2100.

18.4 Concluding Observations

There is a wide range of projections of relative SLR for Miami for the 21st century. The range ofpotential worldwide SLR by 2100 isfrom as little as 18 cm (7 inches) (*Climate Change 2007*, 2007)to 2 m (6.6 ft) (Pfeffer et al.,2008)higher than today.Pfeffer concludes that the most likely amount of worldwide SLR (global average) from 2000 to 2100 will be approximately0.8 m (2.6 ft).This would result in a relative SLR in Miami of approximately 0.26 m (0.84 ft) by 2050 and 0.82 m (2.7 ft) by 2100 (relative to 2000).

The IPCC Science and Technology Committee states that worldwide sea level will be *at least* 0.9 to 1.5 m (3–5 ft) higher by 2100. Although that amount of SLR is possible, it falls above the amount of SLR considered most likely for Miami by the experts cited earlier. Therefore, as Miami plans for future SLR,itshould, as a worst-case scenario, consider the possibility that relative sea levels may rise up to 1.95 m (6.4 ft) by 2100. However, itshould also consider a SLR of about 0.82 m (2.7 ft) as most probable. There is a lot of uncertainty about the amount of future SLR. Thus, it may be prudent to plan for a wide range of possibilities, rather than fixatingon a specific number or too narrow a range.

Table 18.2. Estimated Total Relative SLR for Miami-Dade

Time Period	Total Subsidence— cm (ft)	Total SLR by Emission Scenario in Centimeters (ft) (relative to 2000)		
		B1	A1B	A1FI
2050	3.49 (0.11)	8.66 (0.28)	16.37 (0.54)	28.21 (0.93)
2100	6.98(0.23)	17.51 (0.57)	40.54 (1.33)	92.24 (3.03)

Chapter 19

Communication Strategies

There are two times whena water resource manager is likely to end up needing to talk about climate change. The first is when a water management decision needs to be made that includes consideration of climate change and it is the manager'sjob to present the issue. For example, if you have decided as an agency to seriously consider adding a reclaimed water program due in part to the need for a climate-independent supply source, you will probably need to discuss if and how climate change considerations impacted your decision. The second is when the issue of climate change has been raised and the manager is asked to address the issue directly (for example, if a local environmental group has asked you to come to a meeting and identify how your utility is addressing climate change).

Reclaimed water programs also require good communication strategies. However, regardless of the situation, good communication requires that you know your audience, that you have an established line of communication that has been utilized to develop trust, and that the message to be delivered is clear. In dealing with the issue of climate change it is also important to have strategies to keep the discussion focused on resource management and away from the politics surrounding global warming.

This section provides a brief overview of effective communication strategies with a focus on climate change and reuse, as well as a discussion of how to keep the conversation focused on resource management.

Regardless of the situation, good communication basics are the same:

- Identify what needs to be communicated
- Identify to whom this needs to be communicated
- Analyze the audience to determine what information they need and how it needs to be presented
- Identify the communication tool
- Communicate
- Measure results

Most large utilities will have a communications department or officer. Be sure towork closely with him or her! He or shewill have lots of good background information that you should capitalize on.

19.1 Define the Goal of *This* Communication

As a first step, it is vital that you identify why you are communicating and the desired outcome. This may seem obvious, but sometimes we forget the obvious. Perhaps you have a need to communicate about a climate-related tipping point you have identified concerning the potential need to site a new reservoir. The goal of this communication is to get the go-ahead to develop an economic feasibility plan that includes these factors. Or perhaps the goal of

thecommunication is to get customers to recognize the need for and value of the new reservoir and agree to a rate increase to pay for it. Both are communications about how changes in climate affect whether and how the new reservoir is sited. But each will have a different audience, require different communication tools, and betargeted with a different goal in mind.

Outcome objectives can be placed on a continuum where the need for a decision lies at one end of the spectrum, whereas at the other end the object is merely to provide information. Inbetween the two end points, the objective is typically a shared communication where the goal is to provide an opportunity for the give and take of information.

19.2 Identify Who Needs *This* Particular Information

Once you have identified the goal of the communication, the next step is to identify who needs the information you are communicating. To follow the current example, when discussing the tipping points, you may need to communicate with all the team members on the siting committee, as well as everyone involved in helping identify the tipping points. The list of water resource stakeholders provided in Figure 19.1 can be used as a checklist to ensure you identify all the groups you need to communicate with.

19.3 Identify Audience Attitudes and Perceptions So That You Can Target the Message

Once the audience has been identified, it is vital to analyze the audience in order to develop a sense of their attitudes and perceptions as related to the goal of the communication. This makes intrinsic sense. If your audience is a group of global climate scientists, there will be no need to discuss why the utility is considering responses to climate change;however, if the audience is likely to include people with a strong belief that global warming is a giant hoax, then you will need to have strategies to keep the discussion focused on good resource management.

- Directly billed water utility customers
- Utility employees
- Utility governing body members
- Environmentalists
- Recreation enthusiasts, including those from outside your service area
- Media
- Schools
- Local university research programs
- State agencies and officials
- Federal agencies and officials
- Regional planning organizations
- Associations, such as historical associations, neighborhood associations, health advocates, and taxpayer groups
- Special population groups, such as racial/ethnic/cultural groups, parents with young children, retirees, people with limited or no English-speaking skills, or people with physical, mental, and sensory disabilities

Figure 19.1.Potential audiences and water resource stakeholders.
Source: Mobley et al., 2006.

Existing data can be used to create an initial picture of your target audience. Sometimes this is as simple as asking members of a small, intimate audience what they already know and what they hope to learn. For larger, ongoing communication strategies, primary research, including focus groups, literature reviews, and consultation with experts or surveys,isnecessary. The amount of available resources and the importance of the communication will dictate how much research is required.

The goal of audience research is to develop an understanding of your audience, including

- The range of attitudes about climate change, as well as the predominantone
- The range of attitudes about reuse, as well as the predominantone
- The amount and type of background information they will need to follow the discussion
- Their primary concerns about the issue
- Their level of trust both in you as a communicator and in your ability to do what you are communicating (for example, to appropriately site the new reservoir)

The attitude and perceptions research findings will help you determine if you need ongoing communications, if you need communications that are segmented into smaller units with specific messages tailored to specific groups, and the general level of background information necessary for the communication to be clear and understandable by the audience.

Knowing theaudience and responding to that information is the single most important aspect of communication!

19.4 Identify a Communication Tool, Communicate, and Measure Results

This section of the primer is not designed to help you build a strategic communication plan. [If you are considering a long-term strategic communication campaign, review the AWWA Research Foundation paper *Strategic Communication Planning: A Guide for Water Utilities* for further ideas (Mobley et al., 2006)]. Rather, it is designed to remind you of the basics of good communication and provide insights into how to discuss climate change without getting bogged down in politics. Therefore, the discussion ofidentifying communication tools and communicating and measuring results is brief.

Communication tools run the gamut fromchatting with someone in the hallway (not always a bad approach to getting hold of that elusive co-worker) to creating an ongoing strategic multimedia campaign. When selecting the communication tool, consider the time allotment, in terms of both how long the audience is available and how long the message needs to be; the space (if you want to give a power point presentation make sure that computer facilities are available); and how well your choice of tool meets the needs of your audience.

During the communication process, stay focused on good resource management!

Remember that because communication is between fallible human beings, no communication effort will ever be perfect. Therefore, it is important to learn from the past so that you can improve the future. Be sure toidentify how you will measure success before your communication.

Chapter 20

Common Questions, Misconceptions, and Practical Realities

This chapter attempts to provide some pragmatic advice and approaches for W/WW utility planning in the face of potential climate change, with a focus on issues related to water reuse. Each topic area is posed as a question, under which the responses include both a "common misperceptions" section (intended to dispel myths and alert utility readers about typical mistaken impressions) and a section on "practical realities" (intended to provide practical guidance and insights).

1. *When Should Utilities Consider Climate Change within Their DecisionMaking Processes?*

Common misconceptions: Climate change is a separate issue from the day-to-day planning activities of the utility. Climate change requires a special analysis, and will be distinct from the utility's routine business and decisionmaking processes.

If a utility engages in a special climate change study, it will obtain a set of useful and unambiguous projections regarding future precipitation patterns, stream flows, water demands, and other climate-related variables that drive utility planning efforts. These climate change projections can then be plugged into a utility's traditional planning formulas and models to anticipate future water demands, water supply yields, treatment needs, and so forth.

Practical realities: Utilities need to factor climate change considerations into their routine programmatic decisionmaking processes. This is particularly relevant to major capital improvement program (CIP) projects, especially for those options that represent long-lived investments that would be difficult and expensive to modify or replace within their anticipated economic asset lives. During the course of their routine project evaluation processes, utilities need to consider how climate change may impact these investment decisions.

Utilities already make key decisions about the future on a routine basis (e.g., periodic assessments of future water supply and demand) in order to determine what new investments need to be considered and pursued (e.g., acquiring additional source waters or developing storage to expand the capacity of the water supply portfolio to meet anticipated demand growth). Because such investments are expensive and long-lived, careful planning needs to be done in order to ensure that the right investment decisions are made.

Further, because the future is inevitably uncertain, these investment decisions need to be considered in the context of risk management. For example, investing too little in future water supply enhancements means that future needs may not be met; and, alternatively, investing too much will likely result in expensive stranded assets.

Most utilities already engage in some form of risk management and business case evaluation (BCE)—such as using benefit–cost, TBL, or some other form of formal analysis—to evaluate, rank, and select CIP options. They do this at routine utility decision points as they arise. Climate change needs to be considered within this in-place project evaluation framework, and a pragmatic approach todoing so is suggested in the following discussion.

2. *How Should Utilities Apply Climate Change Projections?*

*Common misconceptions:*Results from climate change modeling efforts will provide new parameter values for key climate-related variables. These results can then be used as input values that the utility (or its consultants) can simply plug into the utility's traditional planning models. The utility planning process and toolkit remain largely unchanged, and all that is altered is the input values for several key climate-related planning variables (e.g., annual average and/or seasonal precipitation levels in future years).

This view is often referred to as the "top-down" approach, because it presumes that climate change impacts can be forecast reliably, and then utility planning efforts simply take these projections as input values and proceed as usual. Several climate-related key input values are presumed to change (i.e., the climate change projection models provide the inputs at the top of the process), and these climate change-based values are fed downward into the traditional utility models and decision-making processes as inputs.

*Practical realities:*As detailed in the next sections, there is a high degree of uncertainty about how climate change will impact utility-relevant planning parameters. In some cases, the range of projected outcomes across all the available climate models and emissions scenarios can be so broad and contradictory (i.e., it may be either a lot wetter or a lot drier) that it can be unhelpful for future utility planning. For this reason, we recommend a *bottom-up*or*reverse engineering*approach, coupled with a careful selection of climate change impact projection *scenarios* (as described in Question 5).

We suggest that utilities *not* rely on highly uncertain and wide-ranging top-down climate change projections. Instead, we recommend that utilities start from the perspective of (1) defining what decisions need to be made (i.e., what CIP projects to pursue, and which options to select) and then (2) determining what information is needed to make those decisions prudently (and the level of precision required for that information). This is a reverse engineering or bottom-up perspective. Once the decision-relevant information needs are identified, the utility can focus on obtaining the right data (e.g., identifying what climate change scenarios to consider within their CIP project evaluation process).

A key merit of this recommended bottom-up planning approach is that it enables utilities to rely primarily on what they already know best (e.g., their internal models, working knowledge, and planning processes). From this base of knowledge and experience, the utility can then consider if and how climate change may impact itssystems. This bottom-up approach relies primarily on existing utility models and project evaluation and planning processes.

As noted previously, most utilities already routinely engage in some form of systematic evaluation (e.g., a form of BCE using TBL or benefit–cost analysis) to conduct formal analyses to evaluate, rank, and select CIP options. To consider climate change impacts within this existing evaluation framework, the following pragmatic approach is suggested:

1. Focus on expensive, long-lived investments (e.g., water resources, treatment plant process selection, sizing and location, distribution and pumping), with potentially significant implications if climate change may render an expenditure unwise (e.g., stranded assets) or inadequate (e.g., chronic water shortages). These are the decisions where the stakes are highest (i.e., where the cost of making a poor decision islikely to be highest).
2. Start with a standard BCE of a potential investment, assuming initially that climate does not change. Identify which options under consideration look justified (e.g., have positive net benefits) and how the options rank compared to one another (which option appears to be the best choice, which ranks second, and so forth).
3. Then consider how the BCE might be altered if some key climate-related parameters were altered (using a well-defined set of relevant climate change scenario projections). This is a relatively straightforward form of *sensitivity analysis*.
    a. Determine whether the results of the evaluation change when climate change is included within the assessment (Does the ranking of options switch? Do net benefits for the top options change from positive to negative, or vice versa?).
    b. If the results (rankings, net benefits) are not appreciably altered under applicable climate change scenarios, then proceed as usual. In this type of outcome, the decision the utility is inclined to make without considering climate change is also likely to be a sound choice under the relevant climate change scenarios. This is often referred to as a *no-regrets* option, because the utility will not regret the decision, even if climate does not change as anticipated.
    c. If a climate change scenario(s) alters the ranking of options, then a more in-depth evaluation may be prudent. For example, it may make sense to view the potential investment through an *adaptive management* lens (as described next), such as considering if the decision can be phased in or delayed until better data, information, or trends become evident.
4. Alternatively, at step 3, consider what changes in key climate-associated parameter values would need to occur to alter the top option rankings and/or switch the estimated net benefits from positive to negative (or vice versa). Determining the parameter value(s) that alters the BCE findings in this manner is called a *tipping point* or *threshold value* analysis.
    a. The utility can then examine a range of carefully selected climate change projection scenarios to determine whether it seems likely that the tipping point values will be exceeded during the relevant planning horizon.Suppose for example thata key tipping point for future water supply shortfalls is reached if summer season precipitation decreases by more than 40% before 2050. Given this finding, the utility can scan applicable climate change projections to determine whether such a 40% or greater decline is projected within the suite of relevant climate change projection scenarios.
    b. If the tipping point or threshold value is not projected to be exceeded (or appears highly unlikely to be exceeded) within the planning period, then proceed as usual.

c. If an applicable climate change scenario projection(s) reveals that the threshold value may be exceeded, then a more in-depth evaluation may be prudent. For example, it may make sense to view the potential investment through an adaptive management lens (as described later), such as considering if the decision can be phased in or delayed until better information or trends become evident.

3. *Where Do Climate Change Projections Come From?*

*Common misconceptions:*There is a well-accepted model(s) of global climate that can be used to reliably predict future conditions. As a utility, we can obtain climate change projections for our watershed and service area. Based on these projections, we can plan for how we meet future needs. The climate change inputs to our planning exercises are no different from how we obtain and use projections of future population levels in our service area. For example, we can easily use climate change model projects as inputs to determine which water supply expansion projects (if any) we need to pursue (and when) in order to meet projected future demands.

*Practical realities:*Climate scientists, computer programmers, and other researchers around the world have been developing and refining what are referred to as atmosphere–ocean general circulation models (AOGCMs), often referred to more simply as GCMs. These complex models simulate the climate of the entire Earth, typically dividing the world into grid boxes that can be several hundred miles across. The models estimate how climate may change with increased GHG concentrations.

Currently, there are nearly two dozen large complex GCMs that IPCC determined to be of sufficient quality to use in its Nobel prize-winning *4th Assessment Report* on climate change (*Climate Change 2007*, 2007). The outputs from these multiple GCMs are an integral part of the climate change projection and planning process, yet the GCMs can yield widely varying results (especially regarding changes in precipitation).

The results of any GCM are further influenced greatly by the CO_2 (i.e., GHG) emissions scenario fed into the model. The GHG concentrations that are input to the GCMs are themselves derived from a range of "emissions scenarios" that attempt to convey the level of global emissions of GHGs anticipated over the course of the 21st century. Different emissions scenarios reflect a range of assumptions about the pace and types of global population growth, economic development, and technological change.

There are several difficulties water utilities have with using GCM outputs in their planning and decision-making. One challenge is that the range of outcomes generated across the 20+ available GCMs are widely variable, and the models often disagree with each other on key outcomes such as annual precipitation. For example, half the GCMs show the Denver area as having increased precipitation and the other half show decreased precipitation. Further, the uncertainty range is broader than the range of GCM-generated outputs.

Another critical challenge for water utilities is that the GCM projections are for areas much larger than a typical water utility's planning scale. To overcome the large geographic scale of GCM outputs, these results can be "downscaled" to smaller geographic areas. There are two basic downscaling approaches: (1) statistical downscaling, which relates climate on a much finer scale to projections from GCMs, and (2) building much higher-resolution RCMs. Both approaches yield projections at a scale more useful for utilities. However, both approaches must use GCM outputs. If the GCMs do not accurately project changes in climate, then the

downscaling options will not improve the projections. Further, by adding a modeling layer to the GCMs, the downscaled results can have a higher (compounded) level of uncertainty associated with them than the GCM results themselves.

In general, utilities would prefer to have agreement across the GCMs on future changes in key variables such as precipitation and temperature at spatial and temporalscales consistent with utility planning and management models. This agreement would involve first getting the climate models to consistently show increases or decreases in key variables, and then narrowing the range of projected changes. Utilities are also interested in having projections of climate change that are consistent with their planning horizons. However, it may be many years (perhaps a decade or more) before such improvements in the GCMs models and emissions forecasts are able to yield such agreement and confidence in results.

4. *Why Are Climate Change Projections So Uncertain?*

*Common misconceptions:*Climate change projections are inconsistent and uncertain because the scientists generating these results have their own agendas to promote, and benefit from the scary outcomes their projections generate (e.g., they promote more funding for climate science and modeling). Remember that in the 1970s, scientists warned us about impending global cooling! Do not trust the scientists or their models.

Also, Earth's climate has always been changing, as part of the planet's cyclical pattern in which the globe routinely alternates between warm and cool periods (e.g., the ice age) over long spans of geologic time. Climate patterns we have observed over the latter half of the 20th century and through the first decade of this century may be more noise than signal. If these patterns do indicate an emerging change in climate, it is probably part of the planet's natural cycle.

*Practical realities:*If a wide range of climate change models and emission scenarios are used, one can expect to derive a widely divergent range of projected outcomes for utility-relevant climate parameters (notably, average annual precipitation). Thus, there is a high degree of uncertainty about how climate change will impact utility-relevant planning parameters.

Key uncertainties in the outputs from climate change modeling arise in at least three stages of the process:

1. Global model projections. There are more than 20 well-regarded GCMs that are widely used in developing projected changes in global climate (additional detail is provided later). These GCMs generate widely divergent projections about changes in annual average precipitation across regions, with several GCMs typically indicating an increase for a given region, and the other GCMs predict a decrease.
2. GHG emission-level projection scenarios. The GCM-based uncertainty is compounded because the GCMs results are driven—and significantly impacted—by the choice of GHG emission scenario applied. Numerous official GHG emissions scenarios have been developed to reflect alternative assumptions about the levels of future GHG emissions (the scenarios reflect different assumptions about the levels, distribution, technology mix, and other characteristics of economic activity through the 21st century).
3. Downscaling to a relevant geographic scale. The GCM outputs are generated on a very large (e.g., subcontinental) geographic scale that is at too coarse a level of spatial resolution to be of direct value for W/WW utility planning. Various forms of

downscaling of GCM outputs have been developed and may be used to generate climate-related projections at the watershed and regional scales relevant for utility planning (e.g., statistical downscaling, bias correction). However, each of the various downscaling and regional climate change modeling approaches adds additional layers of uncertainty to the GCM projections.

When these three uncertainty-generating facets are compounded, the resulting range in projected climate change impacts can be so large as to render them of little value for practical utility planning purposes.

5. *What Climate Change Projections Should Utilities Use?*

*Common misconceptions:*There are two types of potential misconceptions regarding future climate change and its impacts. The first misconception is that a utility can use the observed record (e.g., the past 50 years of observed data on precipitation, aquifer recharge, stream flows, reservoir levels) to project what the coming 50 years will be like. This is known as assuming stationarity in climate. However, recent scientific evidence indicates that "stationarity is dead" with regard to water resources), meaning that it is imprudent for a water planner to assume the future will be a repeat of the past.

The second misconception is that a well-defined suite of useful climate change projections can be taken readily from a broad suite of paired GCM–emissions scenario outputs. As noted previously, GCMs outputs are diverse, and downscaling to suitable spatial scale adds to the high degree of uncertainty in the project climate change variables (especially precipitation).

*Practical realities:*Despite the broad range of uncertainties spanning across climate change projections that originate in the suite of available GCMs, thereis readily available information that, when used with due prudence, can be highly informative. We recommend that utilities examine climate change projections by focusing on results for a carefully selected suite of different climate models (and associated emissions scenarios) as "scenarios." Such *scenario-based analyses* generally do not attempt to assign probabilities or even qualitative likelihoods to the different scenarios; instead, the scenarios are used to create a range of possible future climate outcomes that can be used to investigate potential vulnerabilities and adaptation strategies.

Further details on climate models can be found in Chapters 4 and 5.

6. *Where, and How, Should Utilities Acquire Climate Change Projections?*

This question is so large that an entire chapter has been devoted to answering it. Please see Part I for a background discussion and Chapters 4 and 5 for greater detail.

7. *How Does a Utility Identify and Clear Applicable Institutional Hurdles?*

*Common misconceptions:*Utilities need to plan and operate as defined by current regulatory limits and institutional constraints.

*Practical realities:*If you see a regulatory or other hurdle that would be an impediment to a good reuse planning approach, start efforts to get it modified now, so that you may be able to proceed in the future. Not all institutional hurdles can be changed, but with lead time and well-focused collaborative efforts, state and other regulators often are willing to see where

current rules may inhibit sound practices and thus be willing to consider modifying them. Examples include ASR approval for Phoenix reuse project, IEUA getting the Water Quality Control Board (WQCB) to relax a prohibition on reuse applications that recharge the local aquifer, and El Paso getting regulatory leeway for deep-well injection of inland desalter concentrates.

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Appendix A

Case Study: Miami-Dade Water and Sewer Department

A.1 General Overview of Utility

MDWASD is a W/WW utility located in southwest Florida. The primary responsibilities of this retail and wholesale provider include water treatment, transmission, and distribution, as well as sewer collection, treatment, and disposal. The MDWASD utility system is shown on Figure A.1.

MDWASD operates as an enterprise fund of Miami-Dade County. It funds its expenditures through retail and wholesale charges and receives no income from ad valorem taxes levied by the county (Malcolm Pirnie, 2007).

On the average, MDWASD serves a population of 2.2 million. It is ranked as one of the 10 largest W/WW utilities in the United States based on population served, number of accounts, and amount of water sold (AWWA and RFC, 2009) and is the largest water utility in the southeastern United States (Malcolm Pirnie, 2007).

A.1.1 Water Supply Sources, Treatment, and Distribution

A.1.1.1 Water Utility

MDWASD's water system, which has a permitted capacity of 452 mgd, serves approximately 418,000 retail customers and 14 municipal wholesale customers located within Miami-Dade County (Miami-Dade Water and Sewer Department, 2009). MDWASD sells approximately 56% of its water to retail customers; 22% is sold to wholesale customers, with the balance being nonrevenue water. The majority of water utility retail customers include residential single-family (89%), followed by nonresidential (8%) and residential multifamily (3%). Nonresidential customers include government entities, hospitals, and commercial and industrial facilities. MDWASD's retail customers include special accounts for residential sprinklers, nonresidential sprinklers, mixed use (residential and commercial) properties, and marinas (Malcolm Pirnie, 2007).

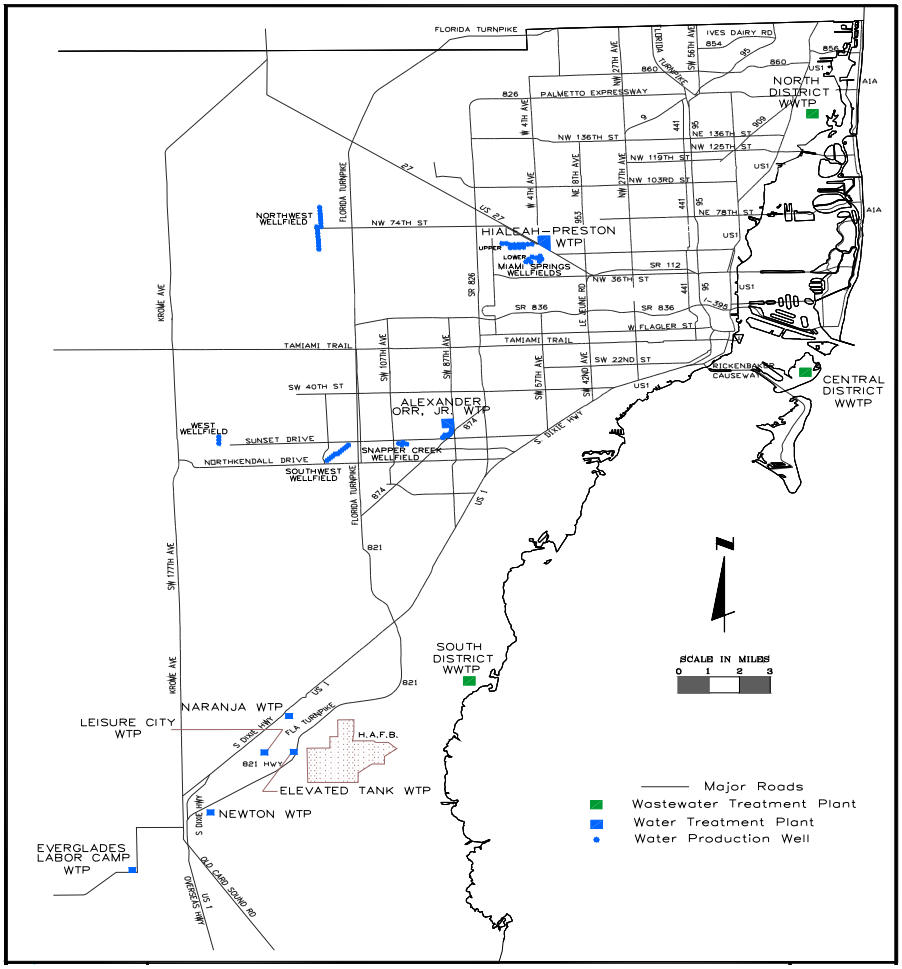

Figure A.1. MDWASD system.

Source: MDWASD Water Production Division.

The primary raw water source is the surficial Biscayne aquifer, a nonartesian (or near-surface) aquifer that underlies an area of about 3200 square miles in Miami-Dade, Broward, and Palm Beach counties. Raw untreated water is supplied to the treatment facilities from 14 major wellfieldscomprising 94 individual wells and 5 aquifer storage and recovery wells. The water treatment system consists of three regional WTPs: the Hialeah, Preston, and Alex Orr, Jr., WTPs. These plants serve an area of more than 400 square miles in the north and south areas of the county. Five small auxiliary treatment facilities, referred as the South Dade Water System, serve the southernmost part of the county (Miami-Dade Water and Sewer Department, 2009).

The regional facilities treat the water using lime softening processes that include recarbonation, filtration, and chlorination or chloramination for disinfection. In some instances, conditioning agents such as phosphate are used to further enhance the treated water's stability and aesthetic quality. The Hialeah and Preston plants also use air-stripping packed towers to remove volatile organic compounds (VOCs). The South Dade Water System uses disinfection and conditioning agents for treatment.

Treated water is distributed throughout the service area (more than 400 square miles) via seven remote finished water storage tanks and 7559 miles of water mains, ranging in diameterfrom 2 to 72 in. The majority of pipes range between 8 and 10 in.in diameter. Storage criteria are based on the ability to provide sufficient fire flow, emergency storage, and equalization storage (Miami-Dade Water and Sewer Department, 2009).

A.1.1.2 Wastewater Utility

The wastewater system, with a total permitted capacity of 368 mgd, serves approximately 336,000 retail customers and 12 wholesale customers, consisting of 11 municipal customers and the Homestead Air Force Base (Miami-Dade Water and Sewer Department, 2009). MDWASD treats approximately 45.4% of the wastewater from retail customers and 22.7% from wholesale customers, with the balance being infiltration and inflow (I&I). Similarly to the water's retail customers, MDWASD wastewater's retail customers are mostly residential single-family (89%), followed by nonresidential (8%) and residential multifamily (3%) (Malcolm Pirnie, 2007).

The wastewater system consists of three regional WWTPs, the North, Central, and South District WWTPs; 1035 sewage pump stations; and nearly 6200 miles of collection and transmission pipelines. Treated wastewater from the North District and Central District plants is discharged into the Atlantic Ocean. However, in 2008, the State of Florida passed legislation mandating a phase-out of all ocean outfall flows in an effort to terminate this practice, as described in Chapter 9. The South District Plant disposes of its effluent to the lower Florida aquifer at a depth below 2400 ft through deep injection wells. During the past 10 years, the department has constructed five additional deep injection wells as part of its 112-mgd plant expansion project. However, to date only one of these wells has received an operational permit (Miami-Dade Water and Sewer Department, 2009).

A.1.1.3 Existing and Planned Water Reuse Programs

MDWASD began investigating reuse options in 1990 and has since been reusing reclaimed water for a variety of purposes. Currently, MDWASD is using reclaimed water as process water in several WWTP processes, replacing and conserving potable water. MDWASD also reuses 13 mgd of treated wastewater for on-site processes, for landscape irrigation at two of itsWWTPs, and for public access irrigation at Florida International University's Biscayne Bay Campus. The department is also considering using up to 90 mgd of reclaimed water for cooling at two local power plants (Miami-Dade Water and Sewer Department, 2009).

MDWASD has committed to reclaim approximately 170 mgd of wastewater over the next 20 years through a number of projects, including aquifer recharge, irrigation, and coastal wetlands rehydration. Example projects include constructing the South District Water Reclamation Plant to recharge the Biscayne aquifer and the regional water system in the vicinity of the Miami Metro Zoo; providing reclaimed water of public access quality for irrigation projects; testing the feasibility of providing highly reclaimed water for the rehydration of the Biscayne Bay Coastal Wetlands; and recharging the Biscayne aquifer and the regional water system through a new West District Water Reclamation Plant in western Miami-Dade County (Miami-Dade Water and Sewer Department, 2009).

A.2 Background on the Regional Setting in Which the Utility Operates

A.2.1 Population

Over the past 20 years, the regional population has grown at an annual average rate of 1.6%. However, the total average water demand remained constant from 1994 to 2005 because of the per capita use reduction that resulted from implementation of various conservation measures. It is projected that MDWASD's service population will grow by approximately 500,000 people by 2025, corresponding to a 21% increase. As a result, the development of new water sources and efficient use of the existing sources through conservation and water loss management, and maintaining reasonable water rates, will be necessary(Malcolm Pirnie, 2007).

A.2.1.1 Water Supply Considerations and Key Factors Impacting W/WW and/or Reuse

The key regulatory and institutional factor impacting reuse is the State of Florida's formal state objective of encouragingand promotingreuse, as codified in Section 403.064(1), Florida Statutes (F.S.), and Section 373.250, F.S. In response, the Florida Department of Environmental Protection (FDEP) developed extensive rules dealing with water reuse [Chapter 62-610, Florida Administrative Code (F.A.C.)]. Other key regulatory factors impacting water supply and wastewater treatment are the CERP, the RWA Rule, and the Florida Ocean Outfall legislation.

A.2.1.2 Comprehensive Everglades Restoration Plan

SFWMD is responsible for managing the water resources in south Florida. The District designated Miami-Dade County as a "critical water supply problem" area, based on projected population growth of 21% by 2025 for Miami-Dade County and expected negative impacts of pumping the Biscayne aquifer to surrounding natural areas (EEI, 2007). In fact, so much water was diverted from the southern Everglades for flood control purposes and municipal and agricultural supply that significant ecological damage has been done. To rectify this situation, the state of Florida and the federal government have created the CERP, which is managed by the SFWMD. The CERP's main goal is to increase freshwater flow to the southern Everglades by restoring the natural sheet flow and by improving the quality, quantity, timing, and distribution of water in the Everglades (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).

A.2.1.3 Regional Water Availability Rule

The RWA Rule was promulgated by the SFWMD in 2007 to limit raw water withdrawals from the Biscayne aquifer. The RWA Rule was developed to meet water management requirements under the CERP and to enhance the development of alternative water supplies by local utilities. Per the RWA Rule, future water demands that are above and beyond a pre-2006 historical average base pumpage level will be supplied from alternative water sources, such as aquifer storage and recovery, reclaimed water, desalination, and regionalization or offset with wastewater reuse and/or stormwater recovery (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).

A.2.1.4 Florida Ocean Outfall Legislation

In 2008, the State of Florida passed Senate Bill 1302, which requires that the six ocean outfalls used to dispose of treated wastewater along the southeast coast of Florida be abandoned by 2025 and that at least 60% of the water formerly discharged be further treated and reused. This legislation still applies. In February of 2011 Senate Bill 76 Relating to Domestic Wastewater Discharge/Ocean Outfalls,which would postpone the dates of the ocean outfall ban, was filed, but died in Budget. Currently, MDWASD operates two of these outfalls, one at the North District Plant and the other at the Central District Plant. MDWASD has to submit a plan to the Florida Department of Environmental Protection (FDEP) by July 2013 that describes how the outfalls will be removed from use for wastewater disposal. In addition, changes to MDWASD's wastewater collection system and, more importantly, substantial changes to the treatment process that will make the reclaimed water suitable for reuse will be warranted. The capital costs associated with these changes could exceed $4 billion. Although the planning, design, land acquisition, and construction for some of this work havebeen envisioned as part of the 20-year water use permit, removal of the outfalls was not contemplated when the permit plan was prepared and must be reevaluated in order to consolidate regulatory regulations cost effectively (Miami-Dade Water and Sewer Department, 2009).

A.3 Current Regional Water Resource Issues and Challenges Absent Climate Change

Miami-Dade's geographic location, low topography, porous geology, subtropical weather patterns, and proximity to the ocean make for a highly complex, interdependent, and interactive system. Demands for potable water and for agricultural and landscape irrigation must be balanced with the needs of the natural environment (e.g., the Everglades, coastal and freshwater wetlands, and the coastal marine habitat), all of which are intricately linked through the hydrological cycle and affected by groundwater and surface water management, flood control, and wastewater management (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).

A.3.1 Quantity/Scarcity Issues

MDWASD's primary potable water supply source is the Biscayne aquifer, one of the most productive freshwater aquifers in the world because ofits high porosity and transmissivity. Moisture from the heavy rainfall (55 to 60 in.annually, though up to half may be lost by evapotranspiration) rapidly percolates through this porous sand and limestone aquifer. In addition to rainfall, irrigation, surface water in canals and ponds, and groundwater inflow from the Everglades recharge the Biscayne aquifer. Groundwater generally flows from the Everglades southeasterly to the Atlantic Ocean. Freshwater withdrawals from wellfields in the aquifer are the primary source of potable water (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009). Figure A.2 depicts the general hydrology of this area.

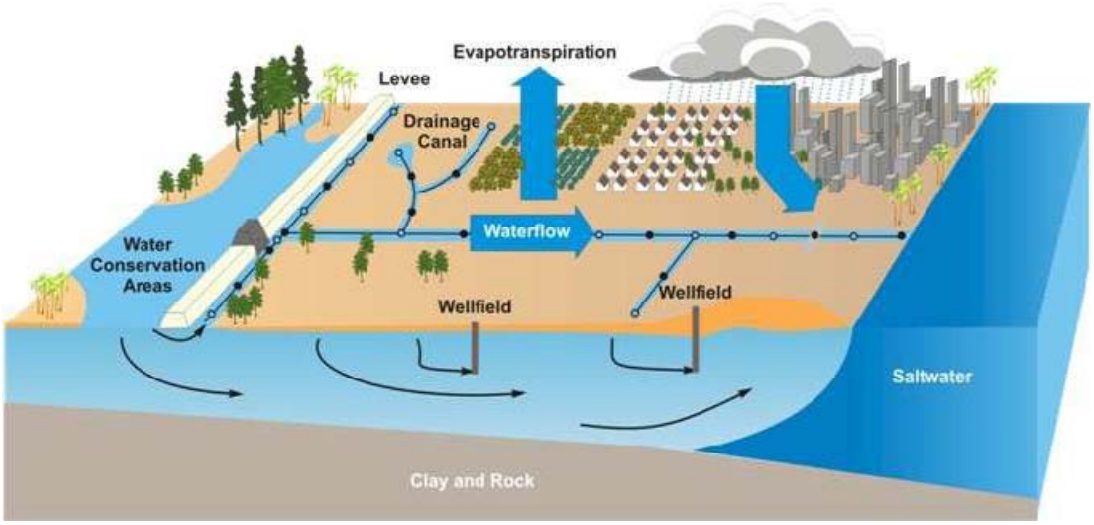

Figure A.2. Schematic of southeast Florida's hydrology.

Source: USACOE and SFWMD, 2009.

The region's highly seasonal rainfall pattern and limited surface water storage, the result of the flat topography, create a significant challenge to balancingyear-round water supply and demand. The high storage capacities of the Biscayne aquifer and the Everglades arelimited by the potential flooding of low-lying terrain. In addition to providing flood control, southeast Florida's extensive system of manmade canals, retention ponds, and lakes provide some capacity for shallow surface water storage. Ending the wet season with high groundwater levels (to maximize storage for the dry season) can be a significant risk if late-season storms develop.

The length of the rainy season is influenced by the Bermuda High pressure systems that develop during the summer (Twilley et al., 2001). If the Bermuda High remains strong through the summer, the wet season is delayed and there is drought. The El Niño/Southern Oscillation (ENSO) also significantly influences Florida's climate. El Niño episodes, which stem from the development of abnormally warm sea-surface temperatures across the eastern tropical Pacific, are associated with significant shifts in the position of the jet stream over North America and elsewhere. This significantly decreases temperatures in winter and spring in Florida. In addition, precipitation in this area is lower during El Niño, as is the number of hurricanes. During La Niña episodes, there areabnormally lowsea-surface temperatures across the eastern tropical Pacific, causing higher temperatures during fall and winter in the Gulf region followed by higher-than-average temperatures in summer. Although this often contributes to regional drought, the average number of hurricanes making landfall in Florida and along the Gulf Coast is typically higher than during El Niño years (Twilley et al., 2001).

A.3.2 Water Quality Issues

Although water from the Biscayne aquifer is generally of good quality because of natural filtration within the aquifer, saltwater intrusion occurs because of the lowering of water levels in the aquifer. Inland movement of sea water started when the flood control canal system was constructed in the 1920s. This movement continued in the 1980s with a change in MDWASD wellfield operations and changes in the delivery schedule of water. Efforts to increase water levels in the Biscayne aquifer have been implemented, notably because of the CERP.

In addition, groundwater drawn from the western urban areas is high in tannins and other organics that originate in the Everglades. However, these contaminants can be removed using carbon filtration and chemical treatment. Another water quality issue is related to a potential statewide ban on phosphorus. Phosphorus removal from wastewater would be useful and could facilitate the use of reclaimed wastewater and stormwater overflows for Everglades Restoration. However, the cost of facilities needed to reduce phosphorus to the levels desired by regulatory agencies for use in the canals or Everglades would certainly exceed any impacts of banning phosphorus (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009). In addition, the state of Florida and the U.S. Environmental Protection Agency (EPA) are developing numerical nutrient criteria for nitrogen and phosphorus in Florida's lakes and flowing waters, including canals, estuaries, and coastal waters, to protect local ecosystems from the effects of excess nutrient enrichment.

MDWASD's northwest wellfield is located in an area designated by the Florida legislature as the Miami-Dade County Lake Belt Area, an area where limestone rock mining is allowed. Because the wells were at increased risk of coming under the influence of surface water, the SDWA Surface Water Treatment Rule (SWTR) now applies to these wells. Thus, the Florida Legislature recognized the risk to the northwest wellfield and imposed a 15-cent "water treatment plant upgrade fee" for each ton of lime rock and sand sold within the Miami-Dade County Lake Belt Area. The fee, effective January 1, 2007, will be used to fund necessary WTP upgrades for filtration and disinfection processes needed to meet the requirements of the SWTR (Miami-Dade Water and Sewer Department, 2009).

A.3.3 Infrastructure Issues

The most critical issue faced by MDWASD is related to infrastructure issues resulting from stormwater and flood management and SLR. Although this issue is periodic in nature, the potential impacts are severe and thus seen by many as being more critical than water quantity or quality. Stormwater is collected from neighborhood swales, ponds, small lakes, ditches, and small canals that are connected through canals and conduits to the secondary system, which is under the jurisdiction of local drainage districts or city or county governments. This controls the retention and release of stormwater to the primary system, which is operated by the SFWMD. Levels and flows in the primary canals are controlled using flood control structures, which also serve as salinity barriers to minimize saltwater intrusion. During periods of excessive rainfall or in anticipation of major rainstorms or hurricane landfall, levels in the canals and the water table in the Biscayne aquifer are lowered to increase stormwater storage capacity. The key issue in stormwater and flood management lies in how to manage the Biscayne aquifer water levels. It is important to strike a balance between the need to maintain the aquifer capacity versus storing freshwater for possibly higher demands during potentially drier seasons. In addition, the requirements of the CERP program need to be met.

A.3.4 Tipping Points

The following are key tipping points for critical resources identified for MDWASD:

- *Seasonality:* Seasonality will have an impact on stormwater and flood management. It may require increased flexibility, balancing the need to maintain aquifer capacity for stormwater storage during wetter wet periods with the need to store fresh water for possibly higher demands during potentially drier seasons.
- *Saltwater intrusion:* Saltwater intrusion and SLR will result in increased TDS concentrations in water supply sources. As a result, it may be necessary to install additional water treatment processes to provide high-quality drinking water, move regional water fields inland, use supply from a lower aquifer of lesser quality, or expand the stormwater management canal system.
- *State regulation:*The ban on ocean outfalls, coupled with the mandate that at least 60% of the water formerly discharged be further treated and reused, will require changes to MDWASD's wastewater collection system and treatment processes to make reclaimed water suitable for reuse.

A.4 Utility Planning and Management: Issues and Approaches

Florida statutes define a 20-year planning horizon for regional water supply planning and require coordination between the regional plans and local comprehensive plans. The district plans cover, at a minimum, a 20-year time period and must be updated at least every 5 years. The regional plan includes a quantification of the region's water supply needs for at least a 20-year period based on a 1-in-10-year drought scenario. The plan also includes a list of specific water supply development and water resource development project options, as well as the local governments and other water supply entities that should implement each project option (Deyleet al., 2007).

State law dictates a 10-year planning horizon for wastewater treatment facilities. Provisions governing the siting and design of new facilities explicitly require that treatment facilities be capable of withstanding the impacts of a 100-year flood (Deyleet al., 2007).

A.4.1 Utility Approach to Addressing Uncertainty

MDWASD has been proactively dealing with these uncertainties. They have conducted a storm analysis and have considered building new facilities (to counter SLR). In addition, the department has created an Office of Sustainability to increase awareness of water management issues and actively promote conservation. Finally, they have engaged in regional approaches, such as the regional coalition with Broward and Palm Beach counties.

Numerous additional approaches are being considered but have not yet been implemented. These include developing additional water supply options, such as desalination of the upper Floridian aquifer, ocean desalination, decentralization in certain areas to diversify the risk of inundation (the loss of economies of scale may be offset by less pumping and conveyance), and interconnection of collection systems to help mitigate seawater intrusion.

A.4.2 Water Reuse as Part of the Solution to Water Management

To address the key challenges, MDWASD is implementing a water reuse program. In addition, MDWASD has committed to reclaim approximately 170 mgd of wastewater over

the next 20 years to increase water supply, which is being limited by the RWA Rule, and meet water demands. The Department will implement up to five reuse capital projects between 2014 and 2026, including South District Water Recycling Plant (WRP) Groundwater Recharge Phase 1, West District WRP Canal Recharge Phase 2, Central District WWTP Reuse, North District WWTP Reuse, and West District WRP Canal Recharge Phase 3. These facilities will add approximately 60.1 mgd of water supply (Miami-Dade Water and Sewer Department, 2010). The combined projects will cost about $1.6 million, for a total cost per gallon per day of $37.13.

A.4.3 Current Utility Activities/Efforts to Understand and Adapt to Climate Change

Miami-Dade County as a whole has been proactively trying to understand and adapt to the impacts of climate change. In 2007, the Miami-Dade County Climate Change Advisory Task Force was created to advise the County Commission on adaptation strategies. Among their many recommendations, the group recommended that the county should

- Commission the creation of maps that will make it possible to identify areas that will become flooded at different sea levels, providing a basis for assessing risk to development and infrastructure
- Further reduce GHG emissions across all sectors
- Establish a countywide master plan element for climate change
- Fully support CERP to create greater resilience of the natural system
- Review stormwater management operations in order to limit the extent of saltwater intrusion into groundwater and surface water resources
- Convene local and state agencies and water and sewer utilities to discuss climate change and impacts on water quantity, quality, and availability and implications for infrastructure planning and investment

Doug Yoder of MDWASD participated as a member of the Science and Technology Committee of the Miami-Dade County Climate Change Advisory Task Force. This committee found that SLR of 1.5 ft could be expected by 2050 and a rise of 3 to 5 ft could be expected by 2100 (Miami-Dade County Climate Change Advisory Task Force, 2008).

In general, the perception is that climate change is not well understood by the local population. The Office of Sustainability is attempting to create a planning “Green Print” (like a blueprint) to increase awareness. However, it is sometimes challenging to persuade customers that the utility could be subject to water shortages in the future. Fluctuation between drought and flooding make this difficult, especially during flooding events when water seems to be readily available. On at least one occasion, MDWASD had to delay a restriction ordinance because of public response and perception during such a flooding event.

A.5 Impacts of Climate Change on the Regional Environment

A study by the Organisation for Economic Co-operation and Development (OECD, 2008) showed southeast Florida to be oneof the ten coastal metropolitan areas most vulnerable to climate change globally. The area was ranked highly vulnerable in terms of exposed population, which totaled 5.5 million, and the value of exposed assets due to climate change impacts (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).

Table A.1 presents relevant likely climate change scenarios for Miami-Dade County for circa 2050, or 2100, when 2050 projections were not found. Although there is some range in these projections, it is clear that some adaptation measures will be necessary to mitigate the impacts of climate change.

The climate change impacts of most concern to MDWASD are SLR and more intense rainfall events. These impacts are examined further in this section. Vulnerabilityto these impacts could significantly affect coastal southeast Florida, as well as southeast Florida's water supply availability and reliability, water quality, and infrastructure.

A.5.1 Water Supply

The impacts and implications of SLR and more intense rainfall events for water supply are summarized in Table A.2. It is important to note that some can be magnified synergistically when combined.

Although individual rainfall events are predicted to be more intense, climate models tend to project a potential decrease in annual rainfall. However, there is not enough agreement to show a consensus among the models. Impacts may result from the potential decrease in annual rainfall, such as prolonged periods of drought/heat waves and increased demand during the dry/winter and spring season; water shortages for municipalities, agriculture, industry, and the natural environment; reduced river flows; increased demand for irrigation; and reduction in water fire capacity.

A.5.2 Water Quality

The impacts and implications of SLR and more intense rainfall events for water quality are summarized in Table A.3. It is important to note that some can be magnified synergistically when they are combined.

A.5.3 Infrastructure Integrity and Reliability

Saltwater intrusion and more intense rainfall events resulting from a rise in sea level are potential climate change impacts that may affect infrastructure integrity and reliability. Flood control is expected to be the most challenging consequence of these climate change impacts forMDWASD. Such impacts could impair stormwater drainage operations because of degraded water quality and, as a result, require additional treatment and corrosion control. SLR combined with more intense rainfall events/hurricanes can take a heavy toll on coastal areas and the barrier islands in the form of severe beach erosion, coastal inundation, and substantially increased damage from storm surge and wave action. For example, the damage caused by category 5 hurricane Andrew to southern Miami-Dade County wasestimated at $25 billion.

Table A.1. Summary of Climate Change Projections for Miami-Dade County

Parameter	Range	Scale	Timeframe	Source	Comments
Temperature	Increase of between 1.2 and 1.7 °C (2.2 and 3.1 °F) from 1970 to 1999	City of Miami	By 2050–2069	WERF, 2010	Range for scenarios A1B, A2, and B1.
	Continued increase in average regional air temperatures	Florida	Next decades	IPCC, 2007a	More frequent and severe heat vanes resulting in severe drought conditions are projected.
	Increase of 0.12 °C (0.21 °F) per decade	Southeast United States	1956–2005	NCDC, 2010	
	Increase of 2.5 to 3.0 °C (4.6 to 5.4 °F) from 1971 to 2000	Southeast United States	By 2050	NACWA, 2009	Range for medium (A1B) and high (A2) scenarios.
	Increase of 1 to 6 °C (2 to 11 °F)	Global	By 2100	IPCC, 2007a	Magnitude and timing of change will vary by region.
	Increase of 0.13 °C (0.23 °F) per decade	Global	1956–2005	IPCC, 2007a	
Precipitation (characterized by heavy summer rainfalls, corresponding to 70% of annual rainfall)	Decrease of 2.3% to increase of 0.1% from 1970 to 1999	City of Miami	By 2050–2069	WERF, 2010	Range for scenarios A1B, A2, and B1.
	Decrease of 0.6% to increase of 2.2% from 1971 to 2000	Southeast United States	By 2050	NACWA, 2009	Range for medium (A1B) and high (A2) scenarios.
	Decrease of 20% to increase of 15% from 1980 to 1999	Southeast United States	By 2080–2099	IPCC, 2007a	Range from 21 GCMs.
	There is no definitive agreement for predicting changes in precipitation for Southeast Florida between GCMs. In addition, no information was available regarding the potential seasonality of precipitation changes.				
Runoff	Decrease of 10% to increase of 5%	Southeast United States	By 2050	NACWA, 2009	Derived from hydroclimatic simulations from ensemble runs of 12 GCMs.

Source: Draft "Primer for Water and Wastewater Agencies on the Climate Change Projections: How They Are Generated, How They Can Be Accessed, and How They Should Be Interpreted and Applied for Local Water Resource Management and Planning." June 16, 2010. From personal correspondence with Doug Yoder.

Table A.1—*Continued*

Parameter	Range	Scale	Timeframe	Source	Comments
Shift in streamflow timing	Two to five days earlier	Southeast United States	Undetermined	NACWA, 2009	No definitive research is available.
Storm intensity and frequency	Increase in storm intensity but decrease in storm frequency for strongest hurricanes	Southeast United States	Undetermined	Bender et al., 2010	As a result, the strongest hurricanes are likely to have shorter return periods.
	Increase in storm surge (up to 9 feet) predicted by sea, lake, and overland surge from hurricanes model for a category 5 storm	Miami-Dade County	Undetermined	Center for Urban and Environmental Solutions at Florida Atlantic University, 2009	Storm surges are likely exacerbated by SLR.
	Decrease in number of tropical cyclones in total but increase in hurricane intensity, with more category 4 and 5 hurricanes occurring as sea-surface temperature rises	Atlantic and Gulf Coasts	2100	National Resources Defense Council, 2008	This implies potential for extensive wind damage and very high storm surge. Storms of same intensity are likely to cause more damage because of higher sea levels.
SLR	Increase of 1.5 ft Increase of 3 to 5 ft	Miami-Dade County	2050 2100	Miami-Dade County Climate Change Advisory Task Force, 2008	High-end projections. Current rate of increase is 3 millimeters per year according to IPCC.
	Increase of 2 to 4 ft	Miami-Dade	2100	USGCRP, 2009	
	Increase of 0.76 ft	Miami	2050	NACWA, 2009	Projections from five AOGCMs and two IPCC scenarios for Miami using SimCLIM 2050.
	Increase of 0.6 to 6.4 ft with best estimate of 2.7 ft	Southeast Florida	2100	Multiple studies	

Table A.2.Impacts and Implications of SLR and More Intense Rainfall Events for Water Supply

SLR/Saltwater Intrusion	More Intense Rainfall Events
Decrease in freshwater resources	Altered groundwater and surface water quantity
Reduced groundwater flows	Increased sedimentation, which will cause siltation of reservoirs and rivers and in turn reduce storage capacity
Elevation of water tables, which in turn results in reduced capacity of soil to absorb stormwater and increased costs to maintain current levels	Increased flooding because of hurricane storm surge and torrential rains
Increase in flooding risk such as (1) increased levels of interior groundwater and surface waters, (2) reduced groundwater flow through the aquifer, (3) increasingly compromised stormwater drainage systems, and (4) more frequent inundation of barrier islands and coastal areas	Potential increase in the risk of aquifer contamination because of flooding
Aggravated by drought and more intense rainfall	Aggravated by SLR
Implications: • Possible need for new sources of supply • Operational challenges to aquifer storage and recovery and water reclamation facilities	

The primary impacts oninfrastructure integrity and reliability would be

- *Inundation of barrier islands and coastal property because of SLR:* Properties on Florida's barrier islands would be threatened by the impacts of major storms in combination with rising seas. Coastal inundation could lead to population out-migration, resulting in stranded W/WW assets.
- *Inland urban waterways and stormwater drainage:* Canals and floodplains are vulnerable to inundations during heavy rainstorms and would likely be more so in the event of SLR. Surface water management will be a challenge.
- *Property damage that is due to storm surge:* Aboveground structures such as wastewater treatment and reclamation facilities, water treatment facilities, and sewer lift stations are likely to be subject to intermittent flooding from storms and spring high tides. This can disrupt the power supply to water treatment facilities and pumping stations during storms; cause power interruptions lasting days and even weeks; damage water distribution systems; cause catastrophic failure of equipment; undermine and/or expose aboveground facilities; and increase corrosion exposure.
- *Significant loss of coastal structure capacity:*Loss of coastal structures could be significant in the next 20 years as increased infiltration of groundwater into sanitary and stormwater sewers could impact WWTPs. In addition, almost two-thirds of the coastal control structures in Miami-Dade, Broward, and Palm Beach counties are threatened by a SLR of 8 in., which could occur by about 2040. Most at risk are the structures located in southern Miami-Dade County, because of the extremely low elevations of that area. The drainage capacity of the system could decrease because of higher sea levels.

Table A.3. Impacts and Implications of SLR and More Intense Rainfall Events for Water Quality

SLR/Saltwater Intrusion	More Intense Rainfall Events
Higher source water temperatures	
Threat to sensitive ecosystems in the Everglades	
Increased saline intrusion into groundwater and brackish water	• Altered groundwater and surface water quality • Expected degradation of water quality (low dissolved oxygen, bacteria, contaminants, eutrophication, algae blooms) that will require higher levels of water treatment and increase risks to human health
• Altered biology and chemistry of brackish receiving waters because of increased salinity • Expected degradation of water quality (TDS) to require higher levels of water treatment and increase risks to human health	• Altered biology, chemistry, and geomorphology of receiving waters because of increased water temperatures (lower dissolved oxygen and increased acidity) • Increased turbidity and sedimentation in receiving waters • Increased bacterial contamination from upstream facilities overwhelmed by high flows
Temporary contamination of water supply with saltwater	Temporary contamination of water supply with other contaminants because of storm surge Changes in quantity and quality of runoff and in the resulting nonpoint source pollution loads to receiving waters from all land use types
Implications: • Altered process requirements for WTPs • Altered biology and chemistry of receiving water for wastewater treatment and compliance requirements (wastewater and stormwater) • Possible infiltration of poor-quality water into the system (I&I) • Downstream implications of altered wastewater treatment processes on reuse (use of reverse osmosis or saltwater introduction during a storm surge event may take out biological processes), biosolids management and process needs, and overall energy use and carbon footprint	

Overall, these climate change impacts would lead to the following infrastructure integrity and reliability problems:

- Potential flood damage and increased maintenance needs that are due to sediment deposition in stormwater retention facilities
- The need for design modifications to many types of stormwater facilities to accommodate more intense rainfall and runoff
- Increased risk of operational impairment of storm drain outfalls
- Increased risk of direct flood damage to stormwater management facilities
- Increased risk of direct flood damage to treatment plants, pumping and conveyance appurtenances, and outfall and biosolids facilities
- Increased emergency power needs for resiliency in the face of more frequent hurricanes

- Operational challenges to biosolids facilities
- Operational challenges to aquifer storage and recovery and water reclamation facilities

A.5.4 Regional Population and Economic Trends

Miami-Dade County is projected to sustain continuous population growth until 2050. Although not well understood in general, the economic, health, and social consequences of climate change are expected to be significant. In essence, higher atmospheric temperatures are likely to engender prolonged periods of drought and extended heat waves. Thesewill in turn affect water supplies, agriculture, and habitat and likely lead to more wildfires and create increased energy demands and health hazards for young children, the elderly, and the infirm. Other consequences include the potential for insect infestation and insect-borne disease, which would result from increased temperatures combined with increased flooding because of storms; the bleaching of coral reefs and adverse effects on marine life and fisheries because of elevated sea water temperatures, affecting tourism; and ecological changes in the Everglades and other natural systems, affecting plant ecology, wildlife, the marine estuaries and coast, and tourism.

A.6 Potential Roles of Water Reuse in Adapting to Climate Change

A.6.1 Options for Creating or Expanding Water Reuse

In offsetting SLR and drought caused by climate change, it is necessary to provide and maintain as much freshwater in the hydrologic system as possible within the constraints of stormwater management. There are four ways to do this: (1) protect existing water sources, (2) reclaim and reuse treated wastewater for nonpotable supply, (3) develop alternative water sources for potable supply augmentation, and (4) implement stormwater management.

A.6.1.1 Protection of Existing Water Sources

Protection of existing water sources is a high priority in water resource management,becausewellfields in the vicinity of the saltwater intrusion front will become more vulnerable as the sea level rises. Reuse can be used in a number of ways to protect existing resources.

- *Hydrodynamic barriers*can be used to protect against saltwater intrusion in vulnerable wells. Highly treated wastewater is injected into the aquifer downstream of the wellfields. This raises the water table, increasing the hydraulic head between the saltwater interface and the wellfield, and pushes back the saltwater intrusion front. The extent to which saltwater intrusion can be countered is limited by flood control considerations (reduced soil storage capacity will increase the risk of flooding). One method is to use shallow horizontal injection wells, called infiltration trenches. MDWASD has identified four locations along the coast where such wells can be installed.
- *Recharge of the Biscayne aquifer*through surface recharge or direct injection will provide beneficial use but may contribute to flooding during the rainy season as sea level rises. These options could result in extensive water treatment and high cost. A number of rapid infiltration trench (RIT) projects identified in EEI's (2007) reuse feasibility study update would result in direct recharge of the aquifer. In addition, the

canal recharge could also recharge the aquifer and reduce reliance on regional system.

- *Recharge of the lower Floridian aquifer*would be beneficial, with no anticipated adverse impacts from climate change. However, this technique requires higher-cost treatment, it has not been implemented to date, and there are potential environmental concerns.
- *Recharge of the Everglades* with highly treated wastewater may be an attractive long-term solution to help meet CERP goals. Although some future scenarios could warrant discussion of whether this is the most efficient and effective use of limited resources, the reality is that the large investment already made in Everglades restoration would make it difficult to gain support for plans that do not include restoring the natural system to improve resiliency.

A.6.1.2 Reclamation and Reuse of Treated Wastewater for Nonpotable Supply

The primary applications that do not require costly advanced treatment are irrigation and industrial cooling, such as cooling towers in large air-conditioning systems andcooling water for power plants.

- *Irrigation:* The use of reclaimed water for agriculture, golf courses, residential lawns, municipal medians, and other green areas could replace irrigation wells in many communities and reduce the competition for groundwater supplies. SFWMD rules do not currently provide water credits for displacement of irrigation wells, though there have been ongoing discussions of allowing credits to utilities for providing reuse to former large groundwater uses. MDWASD has an existing reclaimed water distribution system that is used for irrigation of municipal golf courses (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).
- *Industrial use of reclaimed wastewater:* MDWASD is considering supplying about 70–90 mgd of treated wastewater to FPL Company's Turkey Point nuclear power plant. FPL has two nuclear power plants at TurkeyPoint and is planning to build two new plants. As more than 60% of the water used in the cooling towers is evaporated, this could be a significant beneficial use (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).

A.6.1.3 Development of Alternative Water Sources for Potable Supply Augmentation

To date, there have not been any discussions ofdirectly augmenting the potable supply with highly treated reclaimed water. However, a number of the recharge options discussed in Section A.6.1.1 could be implemented to increase the reliability of potable water sources.

FDEP concluded that the introduction of wastewater into surface canal systems in south Florida would constitute indirect potable reuse. Therefore, surface water recharge would require full treatment according to state and local standards. A 2006 FDEP report indicated that local benefit would be reduced because a significant amount of reuse water introduced to canals would go to the ocean (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).

A.6.1.4 Stormwater Management

Stormwater could be treated and delivered to Everglades WCAs, where it would be stored and delivered as necessary to the southern Everglades. This action could help with flood control in the increasingly vulnerable low-lying areas west of the coastal ridge, which has the potential to flood because of climate change and SLR. Reengineering the stormwater drainage system would be necessary to collect and convey stormwater to advanced treatment facilities before pumping to the WCAs. The capital and operating costs would be partially offset by negating the need for alternative water supply and recharge facilities (Center for Urban and Environmental Solutions at Florida Atlantic University, 2009).

Furthermore, as sea level rises, significant discharges of stormwater to the ocean and/or the Everglades by pumping will be needed in order to control the water table and surface waters at acceptable levels.

A.6.2 Reuse as Part of an Integrated Regional Water Resource Management Program

Planning for the effects of climate change requires a regional approach because the activities of others can impact MDWASD and vice versa. For instance, pumping and water use in one county can affect the quantity and quality of water for downstream users and can also affect future flood control planning. An integrated regional program can also offer opportunities for developing advanced water treatment technologies and reducing the incremental impacts to water utility rate payers by sharing of costs and risks. By pooling resources in order to undertake major infrastructure projects, the utilities can take advantage of economies of scale. Interregional water planning also makes it possible to prepare for interoperability between districts in the event of extended but geographically disparate drought conditions brought on by climate change.

MDWASD has already entered into a regional coalition with Broward and Palm Beach counties.

A.6.3 Challenges of Reuse

Although recycled water is seen as a stable source of supply, its use presents a number of economic challenges. The net impact on rates for adding treatment and distribution related to reuse seems high when compared to the current inexpensive potable supply, especially for what is an uncertain and highly seasonal demand. This effect is magnified by the limited ability of fixed-income, retiree, and low-income populations to pay for increases. In addition, a reuse supply for outdoor irrigation can appear counter to the messages being delivered with conservation efforts (e.g., curtailing landscape irrigation).

When the economy rebounds, another complicating factor will be the fact that new construction could impact the supply for reclamation plants, as more low-flow fixtures are installed. Some new developments are already being required to install high-efficiency fixtures that are at least 30% more efficient.

The Center for Urban and Environmental Solutions at Florida Atlantic University (2009) study noted the following concerns for wastewater reuse, cited by some southeastern Florida utility directors:

1. The demand for treated wastewater for irrigation or hydrodynamic barriers could be lower than potential production, especially during wet summer and fall months.
2. The Biscayne aquifer may be more vulnerable to wellfield contamination by constituents present in irrigation-quality reuse water because of its high transmissivity.
3. Reclaimed water may contain compounds such as organics, low levels of pharmaceutically active substances (PAS), viruses, microconstituents, and contaminants of emerging concern, all of which are difficult to remove and may pose environmental or public health concerns.
4. Wastewater in Southeast Florida has a high chloride content (> 1000 mg/L) because of sewer line leakages. Unless this leakage can be substantially eliminated, this wastewater cannot be reused for irrigation without reverse osmosis treatment. Saltwater intrusion is thought to be one reason for the elevated chloride content, especially in communities close to the ocean.

A.7 Conclusions

MDWASD is on the path to integrating reuse into itswater management program. Although the drivers for this have mostly been regulatory in nature (CERP, the RWA Rule, and Florida Ocean Outfall Legislation), the resulting projects will help the utility prepare for the effects of climate change. However, there are important complicating factors that could influence the extent to which reuse is used by MDWASD. These factors include the following:

- Infiltration into the Biscayne aquifer system is extremely important for flood and stormwater control during the rainy season when large rainfall events often occur. For this reason, aquifer levels must be kept low enough in rainy months to accommodate this infiltration and provide adequate storage capacity to mitigate downstream flooding. Lowering of the aquifer levels for flood control must be carefully balanced with the need to store as much water as possible in the aquifer to meet the community's need to extract water over the subsequent dry period. The implication for MDWASD is that using reclaimed water for aquifer replenishment may not be a viable strategy in wet periods, because there is a need to keep aquifer storage capacity available for storage of rainy season runoff. This creates a seasonality dimension to when water reuse can be applied for aquifer replenishment and creates an impediment to reuse options.
- Management of the Biscayne aquifer level is also a critical consideration with regard to meeting regulatory requirements for sustaining and restoring water levels in the Everglades. As the requirements currently are established, the utility only receives credit toward its Everglades-related water obligations if the reclaimed water is used to supply or offset current groundwater extraction. Thisextraction occurs at wellfields located in western (noncoastal) portions of the region. Reclaimed water applied to create a seawater intrusion barrier would affect the eastern (coastal) portion of the aquifer and would not be recognized by the regulator (SFWMD) as an Everglades-relevant offset. Thus, the utility has little incentive to apply reclaimed water to seawater intrusion barriers, because itwould not receive regulatory credit toward the utility's Everglades-related obligations. This creates an impediment to an otherwise

valuable potential reuse application. In addition, the stress on the Everglades caused by climate change could place greater quality constraints on recycled water use and recharge.

- Flooding of areas that are currently habitable after SLR will lead to a reduction in irrigation needs in these areas. The consequence for reuse is a potential reduced demand for recycled water in coastal areas. In addition, increased TDS in sewer mains and sewer line leakage that are due to saltwater intrusion and storm surges coupled with SLR could drive up treatment costs for reuse as additional chloride and TDS removal capability will be needed.
- The utility (and the county in general) has focused almost exclusively on SLR as *the* climate change impact of consequence to the region. As a result, the implications of other important climate change impacts, such as changes in the annual and seasonal precipitation patterns, have not been studied as thoroughly. There could be an increased demand for reuse for irrigation because of higher evapotranspiration (temperature effects) and possibly drier conditions (lower precipitation) in the dry season. However, because SFWMD rules do not currently provide water credits for displacement of irrigation wells, the utility has less incentive to develop reclaimed water for this purpose.

Reuse can provide opportunities for utilities in the southeastern United States to plan for mitigating the effects of climate change, but needs to be incorporated into the existing water management structure. Utilities such as MDWASD are trying to balance taking proactive measures with not moving too far too fast. By emphasizing a no-regrets and low-regrets strategy, MDWASD can be responsive both to climate change adaptation needs andto increasing overall resiliency and sustainability. Increased governmental incentives for implementing reuse projects would help offset the barrier of the expected costs for treatment, and help utilities achieve a more sustainable portfolio.

Appendix B

Case Study: Phoenix Water Services Department

B.1 City of Phoenix Water Services Department

This section provides an overview of PWSD relative to the objectives of this research. Specifically, the following sections include a brief description of the existing W/WW system, water supply sources and considerations within the service area, and reclaimed water efforts.

B.1.1 Water and Wastewater Service Systems

PWSD is a city government agency that provides water to more than 1.5 million residents within the incorporated area of Phoenix and (a portion of) the town of Paradise Valley. The city's water service area encompasses approximately 546 square miles.

The city's potable water system includes 6 surface WTPs and about 30 active groundwater wells. The treatment plants and active well network have a total production capacity of close to 700 mgd. The city's plants, wells, and more than 6000 miles of water mains are designed to meet maximum daily water demands.

Phoenix provides water to a number of different entities under a variety of service agreements. The city shares 41% of the Val Vista Water Treatment Plant capacity with the city of Mesa, and maintains wholesale agreements with Scottsdale, Tolleson, and SRPMIC. The city also has an agreement with the Arizona American Water Company to provide potable supplies to the incorporated portion of the Anthem development (located to the north of the city). A transmission line to the area provides Arizona American an emergency backup supply for its system.

In addition to water supply activities, the city treats more than 250 million gallons of wastewater each day, serving more than 2.5 million residents. Phoenix's wastewater system includes two wastewater plants, a reclaimed water plant, and almost 5000 miles of sewer mains.

B.1.2 Water Supply

Under normal, nondrought conditions, Phoenix has access to approximately 500,000 AFY, or nearly 163 billion gallons. The city relies on four primary water supply sources:

- Surface and groundwater from the Salt and Verde River watersheds delivered through SRP
- Colorado River water delivered through the CAP
- Groundwater pumped from city wells
- Reclaimed water

In addition, the city maintains permits to recharge local aquifers with CAP and reclaimed water supplies that are not needed to meet current demands. After this water is stored, it is available for use in future years when additional supplies are needed for operational flexibility, or to meet growth- and/or drought-related demands. To date, the city has stored more than 62,000 AF of CAP water and 119,000 AF of reclaimed water.

In normal supply years, more than 90% of the city's demand is met with surface water provided through SRP and CAP. Though the city has never incurred a surface water shortage, future severe drought conditions in the source watersheds could result in delivery reductions from these projects. The city's well-diversified water resources portfolio, substantial storage in SRP and Colorado River reservoirs, and declining per capita use have provided a buffer that has allowed itto make full deliveryto customers over the past 15 years of dry conditions in the source watersheds.

Updated analyses by the city demonstrate that under normal supply conditions, Phoenix has sufficient sustainable water supplies to meet the requirements of substantial additional growth within the service area. Also, under scenarios thatassume severe shortage conditions in source watersheds, the city would not be faced with a supply deficit before 2020. To ensure reliability of supplies beyond this time frame, PWSD has begun to plan for alternative sources of supply that will further diversify the current water supply portfolio, and help to prevent drought-related shortages.

Sections B.2.3 and B.4.3, respectively, provide more detailed information on the city's current and planned water supply portfolios.

B.1.3 Water Reuse

Currently, more than 90% of Phoenix's wastewater is highly treated and reused for crops, power generation, habitat restoration, and turf irrigation. Recognizing the importance of reuse as a sustainable supply source, the city continues to pursue full utilization of reclaimed water (i.e., reusing 100% of wastewater).

The city's water reuse program for turf facilities was initiated in 2000, with the construction of the 8-mgd CCWRP. The city delivers reclaimed water produced at CCWRP to turf facilities in northeast Phoenix. When the supply of reclaimed water exceeds demand (e.g., because of seasonal variations), unused water is delivered to an on-site groundwater recharge facility. The city plans to construct a second water reclamation plant in north Phoenix in the future.

In addition, Phoenix is a member of the SROG, a cooperative of Valley cities that owns and operates the 91st Avenue WWTP. Treated reclaimed water from this plant is delivered to BIC via the Salt and Gila Rivers, and serves as a valuable source of cooling water for Arizona Public Service's Palo Verde Nuclear Generating Station. Treated wastewater from the plant is also delivered to the Tres Rios Wetlands, which provide advanced treatment.

Phoenix also delivers reclaimed water from the 23rd Avenue WWTP to the RID, where it is used for irrigation. The arrangement with RID allows the city to access additional surface water supplies through the SRP through an exchange agreement, and also generates groundwater pumping credits through in-lieu recharge.

Phoenix's reclaimed water program is described in more detail in Section B.2.3.

B.2 Regional Setting

To better understand the role of water reuse as a component of the city's water supply portfolio, it is important to understand the regional setting in which PWSD currently operates, as well as expected trends and uncertainties. The following provides a background on population and economic growth within Phoenix, water demand and supply considerations, wastewater and treatment issues, and key regulatory and institutional factors impacting water supply and demand, wastewater services, and water reuse.

B.2.1 Population and Economic Growth

With an estimated population of about 1.5 million, Phoenix represents approximately 23% of Arizona's 6.6 million residents. Between 1990 and 2005, the population of Phoenix increased by more than 43% (PWSD, 2006). The greater Phoenix metropolitan area, including Mesa and Scottsdale, grew by more than 65% during this same time period (Sperling and Sander, 2007), making Phoenix and its surrounding municipalities one of the fastest-growing areas in the nation.

Much of the growth in Phoenix occurred between 1990 and 2000. During this time period, the city's population increased by close to 34%. Between 2000 and 2006, the city's population continued to increase, but at a rate of 15% (U.S. Census, 2010). Prior to the economic downturn, it was believed that this rate of growth would continue through at least 2030 (PWSD, 2006). However, as a result of impacts associated with the slowing economy, growth in Phoenix has decreased significantly in recent years.

Since 2007, the Phoenix metropolitan area has experienced significant declines in real estate values, and a largenumber of foreclosures and job losses. However, a recent (November 2009) report by the Urban Land Institute found that "despite speculation to the contrary, the population of metropolitan Phoenix appears to have remained unchanged or has dropped only slightly since 2007, meaning the area could be better positioned for recovery than has been widely perceived." The report suggests that a rebound in Phoenix will be reliant "not on an immediate resumption of rapid population growth, but on creating opportunities for those who have remained in the area" (PR Newswire, 2009).

Until recently, the $140 billion per year Phoenix area economy has predominately thrived on growth. Service industries (including tourism and businesses services) and trade have accounted for almost 77% of the labor force in the Phoenix area in recent years. Telecommunication operations, investment firms, credit card companies, banks, and customer service centers also make up a significant component of the city's economy. Some of the large processing and regional headquarters operations include USAA, American Express, Chase Bank, Bank of America, Discover Card Services, and Wells Fargo Bank. Other industries with a strong presence in Phoenix include high technology and aerospace, film, health services, and government (City of Phoenix, 2010a). It is unclear how recent economic events have impacted the make-up of these different industries.

B.2.2 Water Demand

Total water demand in Phoenix has been relatively stable since 1996 despite a population increase of more than 30% over that period. As a result, per capita water use has declined significantly over that period.

The general reduction in per capita use over the past two decades has largely been due to the more efficient nature of new construction, the use of low-water-using landscapes, increased saturation of water-efficient technologies in existing homes, and decreased turf grass areas. In addition, with the passage of Arizona's 1980 Groundwater Management Act, which was designed to reduce dependency on pumped groundwater within the region, Phoenix has focused on citywide efforts to reduce demand. Specific measures taken by PWSD include managing the distribution system to reduce lost and unaccounted-for water, limiting the amount of water applied to golf courses, parks, and other turf-related facilities, and requiring low-water-using plants in newly landscaped public areas and rights of way, among others.

Today, approximately two-thirds of the water consumed by Phoenix customers is used for residential purposes. About three-fourths of residential water use is attributed to single-family homes, and the remainder to multifamily dwellings and mobile homes. About one-half of residential water use is consumed indoors.

Nonresidential water use accounts for about one-third of the total water use in Phoenix. Within the nonresidential sector, more than half of the water consumed is used for landscaping and other outdoor activities. The balance is primarily used for industrial processes, cooling, and sanitary purposes.

Given changing economic and demographic trends, as well as climate-related concerns, there are a number of uncertainties regarding future water demands in Phoenix. In addition, growth and development within the greater Phoenix metropolitan area will likely impact water demand within incorporated Phoenix. Although there are uncertainties surrounding near-term growth and development, as surrounding communities grow, the importance of Phoenix as the commercial hub of the region may influence the water demands within the city. For example, the city's residential demands may not grow at the same rate as nonresidential water demands because of higher densities within Phoenix, or because of the expansion of the suburban bedroom communities (PWSD, 2006).

B.2.3 Water Supply

As noted in Section B.1.2, Phoenix relies on four primary water supply sources. Surface water is generated from the Salt, Verde, and Colorado River watersheds and delivered via SRP and CAP. Groundwater wells and reclaimed water make up the remainder of the city's supplies. Figure B.1 shows the breakdown of water supply sources based on normal year conditions. Subsequent sections provide more detail on each source [based on descriptions from PWSD's (2006) Water Resources Plan].

B.2.3.1 Surface Water and Groundwater from the Salt River Project

SRP conveys surface water from the Verde River and Salt River watersheds (which lie to the north and east of Phoenix) to several cities within the greater Phoenix metropolitan area. The project consists of six dams, 1300 miles of canals and laterals, and 255 high-capacity wells. Phoenix WTPs receive about 20% of the (approximately) 1 million AF of water delivered by SRP each year. In years with surface water shortfalls, a portion of the supply received from SRP consists of groundwater pumped from SRP wells.

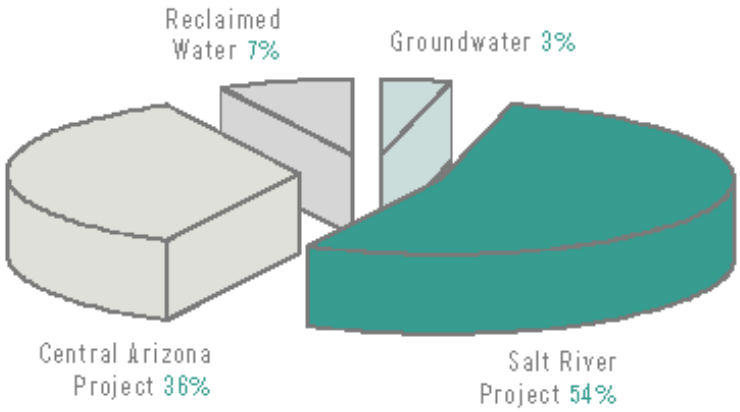

Figure B.1.Makeup of Phoenix water supply sources based on normal year conditions.

Source: PWSD, 2006.

SRP supplies are available only to certain parts of the city, referred to as "on-project" lands. On-project lands (originally farmlands) established rights to the Salt and Verde rivers more than 100 years ago. The city now receives water from SRP at WTPs, and distributes it to on-project lands, which are now urbanized. Some lands continue to receive direct deliveries of nonpotable SRP supplies for urban landscape watering purposes.

SRP has historically managed the reservoir system and its extensive well network to maintain a consistent supply of water to shareholders, despite extreme flow variations in the watershed from year to year. Only twice in the last 100 years (in 1951 and again in 2003–2004) was there a need for SRP to reduce annual allocations to on-project lands.

B.2.3.2 Central Arizona Project Surface Water Supplies

The city has access to approximately 185,000 AF of CAP water per year, available to Phoenix through both long-term subcontracts and leases within Indian communities. CAP conveys surface water from the Colorado River at Lake Havasu, approximately 190 miles fromPhoenix (the system continues another 120 miles to Tucson). The CAP canal was designed to convey CAP's 1.5 million-AF entitlement.

As a result of negotiations involving the authorization of CAP, Arizona agreed that CAP would maintain junior status on the Colorado River, relative to California's 4.4 million-AF allocation. This means that when the federal government deems that there are insufficient supplies available to meet the combined lower basin allocations for Arizona, California, Nevada, and Mexico, the 1.5 million AF associated with CAP willbe cut first (along with deliveries to Mexico and Nevada). The 2007 Colorado River Basin States Agreement prescribes more specifically how shortages will be allocated to Arizona and Nevada based on water levels at Lake Mead.

Water supplies available through both the SRP and CAP systems are based on a wide variety of water rights entitlements, contracts, leases, exchanges, and other mechanisms. These supplies are divided into those that can be used only within areas entitled to receive SRP water, and all other lands within Phoenix. The distribution of these supplies adheres to the legal and contractual obligations associated with each source, but the city's system provides water to all customers in a seamless manner (PWSD, 2006).

B.2.3.3 Groundwater

Under Assured Water Supplyregulations, the Arizona Department of Water Resources (ADWR) allocates groundwater allowances to municipalities. The groundwater allowances can be used at any time and are mostly intended to provide drought relief. Based on groundwater credits validated in the city's most recent Designation of Assured Water Supply, it can pump an average of 40,000 AF per year. Based on currently available well capacity, Phoenix can produce about 30,000 AF per year. Additional pumping credits can be earned through recharging area aquifers.

B.2.3.4 Reclaimed Water

Approximately 40% of water delivered to all Phoenix customers (residential and nonresidential) ends up at one of the city's three WWTPs and is treated for other uses. In total, the city treats about 125,000 AF of wastewater from its service area each year. More than 90% of the treated wastewater is used to meet nonpotable water demands in the region. The following describes the city's current water reuse projects.

North Phoenix Reclaimed Water System. In 2000, the city began delivering reclaimed water from CCWRP to turf facilities (five acres and larger) in northeast Phoenix. Approximately 2000 AF per year has been generated for delivery to those facilities, and the plant can produce up to 8000 AF per year at its current capacity. A recharge facility at the plant provides system flexibility to address seasonal variations in supply and demand. In 2009, this plant was temporarily closed to reduce operational costs, and the wastewater was sent to the 91st Avenue WWTP. The city expects to restart the plant in 2012.

RID/SRP Three-Way Exchange. Phoenix delivers up to 30,000 AF per year of reclaimed water from the 23rd Ave. WWTP to the RID, which then delivers the water to farms. In exchange for this water, RID provides a like amount of groundwater to the SRP canal system. SRP then delivers 20,000 AF of this canal water per year to Phoenix WTPs, and 10,000 AF to SRPMIC. Phoenix may use SRPMIC's unused water in any year.

*Recovery of Stored Effluent.*Effluent stored underground at the RID Groundwater Savings Facility may be pumped by wells that serve the Rio Salado Restoration Project. This water, when pumped, retains the legal classification of effluent. The expected project requirement is approximately 4000 AF per year. The city has stored approximately 119,000 AF of reclaimed water to date.

*Deliveries outside of the Service Area.*As noted in Section B.1.3, Phoenix is a member of SROG, a cooperative of Valley cities that owns and operates the 91st Avenue WWTP. Approximately 20,000 AF per year of reclaimed water from the 91st Avenue WWTP is diverted by BIC under a contract with Phoenix. SROG maintains a contract with Arizona Public Service to provide up to 80,000 AF per year to the Palo Verde Nuclear Generating Station for cooling of reactors. As described later, Phoenix also delivers treated wastewater from the plant to the Tres Rios wetlands.

Tres Rios Demonstration Project. In 1995, Phoenix, in partnership with SROG, USBR, USACOE, and other key agencies and organizations, constructed the 12-acre Tres Rios Demonstration Wetlands Project. The project has recently been expanded to a full-scale facility. The concept originated from a need to find a cost-effective way of treating effluent from the 91st Avenue WWTP to meet more stringent water quality standards for continued

discharge of water to the Salt and Gila River system. The project provides advanced water treatment, enhanced wildlife habitat and passive recreational opportunities. Operation of the wetlands has proved a very successful way of achieving water quality objectives and has been well received by the community. The project has provided habitat for a variety of wildlife species and recreational opportunities, and has garnered support for the full scale project.

B.2.3.5 General Availability and Reliability

Primarily because of Phoenix's diverse water supply portfolio, as well as other factors including decreased per capita use, the city's water supplies exceed current demand. The state of Arizona has granted a "Designation of Assured Water Supply" to the city of Phoenix, affirming that at least 100 years of water is available to serve existing customers. The city estimates that without adding any additional sources of supply and assuming normal supply (nondrought) conditions, it will have enough water to meet the demands of existing customers and all expected growth that will occur in the 50-year planning period. Also, under scenarios thatassume severe shortage conditions in source watersheds, the city would not be faced with a supply deficit before 2020.

Despite the relative abundance of Phoenix's water supply in the short-term, there are a number of uncertainties that the city has begun to plan for in terms of more long-term supply options. These uncertainties include the timing and length of reduced inflows from SRP or CAP, growth and development in the upper Colorado River basin, institutional decisions (e.g., Colorado River negotiations), climate change impacts, environmental mandates, water quality impacts, long-term groundwater availability, and the ability to fund acquisitions and infrastructure (PWSD, 2010).

B.2.4 Wastewater

As noted previously, the city currently treats more than 250 million gallons of wastewater each day (91 billion gallons per year), serving about 2.5 million customers. The extensive wastewater system includes two wastewater plants, a reclaimed water plant, and almost 5000 miles of sewer mains. Key issues associated with wastewater include elevated concentrations of salinity in the wastewater effluent (which has implications for the use of reclaimed water), capacity constraints in areas that are undergoing high-density development, and low flows into the system because of increased water use efficiency. This lastdevelopment, which the city is currently studying through a comprehensive sewer metering project, will likely have profound implications forthe availability of reclaimed water in future years.

B.2.4.1 Salinity

Measured in terms of TDS, salinity occurs naturally in surface water from the Salt River and Colorado River systems, as well as some groundwater areas in central Arizona. Human use introduces additional salinity into the wastewater system, so salinity levels in wastewater and reclaimed water are typically higher than in other sources (City of Phoenix, 2010b). Elevated concentrations of TDS in wastewater can have adverse impacts on wastewater infrastructure, resulting in reductions in the useful life of various system components. Elevated concentrations of TDS in reclaimed water can impede the utilization of this supply for irrigation and groundwater recharge.

In recent years, SROG cities have noted an upward trend in the salinity of effluent generated at the 91st Avenue WWTP. Salinity levels in reclaimed water at the CCWRP (in northeast Phoenix) have also been increasing steadily, largely because of water softener and cooling discharges (PWSD, 2006). Section B.3.2 provides more detailed information on the effects of salinity on Phoenix's water supply, and salinity management within the PWSD service area.

B.2.4.2 Sanitary Sewer Overflows

The city of Phoenix is currently engaged in a major effort to reduce sanitary sewer overflows (SSOs) and to ensure that all parts of the city's wastewater collection system are able to deal with flows in a variety of anticipated circumstances. This effort was undertaken in response to the introduction of more aggressive federal and state regulations regarding the prevention and management of SSOs.

Although the city has worked to design a wastewater network that in most cases has successfully dealt with changes in land use and sewer use,decades of redevelopment, incremental connections to existing sewers, and other changes have left particular segments of the system with little extra capacity to deal with unusual events. The result is that some areas now have limited sewer capacity and are predisposed to SSO events. As a result, the city has had to initiate the construction of new sewer capacity projects and restrict new taps to the system until those projects are completed (PWSD, 2009).

B.2.4.3 Wastewater Flow Volume

In developing reclaimed supplies, the city may be limited by the volume of wastewater flows available. Analysis of the city's wastewater generation volume shows that wastewater flows associated with new development are much lower than state or city guidelines indicate. For example, Arizona Department of Environmental Quality (ADEQ) code indicates an average daily flow from single-family residential units of about 450 gallons. In Phoenix, the actual flow from these single-family residences is only about 146 gallons per day. Thus, the amount of wastewater available for reuse may be much less than originally anticipated.

B.3 Current Regional Water Resource Issues and Challenges

As noted throughout this report, a number of factors contributeto the dynamic environment in which water planning decisions are made in Phoenix. This section both summarizes and highlights key water resources issues related to water quantity, water quality, and W/WW infrastructure.

B.3.1 Water Quality

B.3.1.1 Salinity

Salinity in area source waters is a key consideration in municipal water supply and infrastructure planning in Phoenix. Higher concentrations of salinity are progressively accumulating in the soils and water supplies because of the collective impact of irrigation, urban growth, low rainfall, and high mineral content of geologic features.

Salinity occurs naturally in surface water from the Salt River and Colorado River systems, as well as some groundwater areas in central Arizona. In addition, human use adds salinity to the wastewater system through waste, softener regeneration discharges, industrial cooling,

on-site treatment processes, and a number of other point sources. Thus, salinity levels in reclaimed water are typically higher than in other sources (PWSD, 2006, 2011).

Table B.1. Typical Salinity Concentrations Found in Central Arizona Water Supply Sources

Water Supply Source	TDS (mg/L)
Salt River	580
Verde River	270
Central Arizona Project	650
Groundwater	200–5000
Reclaimed water	Reclaiming water typically adds 300–500 mg/L to source water

Source: City of Phoenix, 2010b.

Table B.1 shows typical salinity concentrations found in waters in central Arizona.

According to the World Health Organization, water with a TDS above 1200 mg/L is generally designated as unacceptable for human consumption because it may cause adverse health effects. At levels in the range 900–1200 mg/L, it can affect the taste and color of water (PWSD, 2011). Although the EPA has not established a drinking water standard for salinity, a secondary (nonenforceable) TDS standard of 500 mg/L has been established. This represents an aesthetic standard, and does not imply any adverse health impacts if the figure is exceeded. Water utilities generally avoid distributing water in excess of 1000 mg/L TDS, as customer complaints (primarily regarding taste) tend to increase at that level (PWSD, 2006).

High levels of salinity reduce the suitability of W/WW for some uses. High-salinity water leaves mineral deposits on municipal and household pipes and fixtures, reducing the expected lifespan of this equipment. High-salinity water can also increase manufacturing costs for some industries. For example, the buildup of salts in cooling towers can increase water usage and may lead to equipment damage.

Salinity can also result in adverse impacts on agriculture and turf grass irrigation. High levels of salinity can reduce crop yields of some plants. As a result, farmers may have to switch to more salt-tolerant crops, many of which require more water, or apply additional water to flush salts below plant root zones. Irrigation of parks, golf courses, and other open space areas with high-salinity water may reduce growth rates in turf and other plants.

In 2001, SROG and USBR initiated the Central Arizona Salinity Study, a comprehensive evaluation of salt impacts in the region and potential mitigation options. The first phase of the study estimated that more than 1.5 million tons of salt enter the Phoenix metropolitan area annually, and that 1.1 million tons are retained in soils, water supplies, and other salt sinks. The report also concluded that high TDS levels in water supplies result in at least $60 million per year in damages. These costs are in the form of prematurely aging infrastructure and appliances, soil additives, water softening, and other related mitigation actions (PWSD, 2006).

Groundwater in the southwest portion of the valley has especially high salinity, with water in the Buckeye area at 2500 mg/L and even higherat times. In a 2003 article put out by ADWR, Steve Rossi was quoted as saying that some of this water could be treated to serve future water demands in the area. He noted that at that time, PWSD had entered into some very

preliminary discussions about a possible regional brackish water desalination plant somewhere in the west valley. The plant would convert brackish water, irrigation tail water, and water from the end of the SRP system to potable water (ADWR, 2003).

Desalination technologies for brackish groundwater are being used effectively in other parts of the Valley, but the major challenge involves disposal of the brine concentrate byproduct. In Phoenix, the concentrate is typically discharged to wastewater systems. This is not an effective long-term solution as it increases salinity levels in reclaimed water, affecting end users of this supply (PWSD, 2006).

B.3.1.2 Additional Water Quality Considerations

First, as a part of recent drinking water standard revisions, the concentration limit for DBPs has been lowered considerably. Phoenix has taken appropriate steps to manage treatment plants and distribution systems to meet these revised standards.

In addition, in recent years, methods of detecting pharmaceutically active compounds in drinking water supplies and reclaimed water have become increasingly sophisticated and have allowed detection at extremely low concentration levels. These compounds are found in reclaimed water supplies and in river supplies that receive discharges from upstream WWTPs. To date, the EPA has not established maximum contaminant levels (MCLs) for these compounds. The city plans to continue to monitor developments in this area.

Finally, aquifer quality standards are becoming increasingly stringent. Treatment of wastewater to even higher levels may become necessary (PWSD, 2006).

B.3.2 Infrastructure

The city's 2008–2013 Capital Improvement Plan was developed based on a budget of $1.5 billion. Aside from the acquisition of additional water resources, and the acquisition, construction, and/or rehabilitation of new groundwater wells and storage reservoirs, no other major activities are anticipated.

The CIP is funded with water operating revenue, nonprofit corporation bonds, impact fees, and City of Mesa participation in the Val Vista Water Treatments Plant joint venture. Major projects included in the most recent CIP are as follows:

*Water supply.*The city plans to acquire and construct new groundwater wells and rehabilitate existing wells, as well as to construct and rehabilitate existing storage reservoirs. In addition, a major activity identified is to "acquire additional water resources." No additional detail on the acquisition of water resources is provided in the CIP.

Infrastructure. The CIP includes rehabilitation of existing infrastructure, including booster stations and steel tanks. The city also plans to perform an assessment study of all prestressed concrete cylinder pipes.

*Treatment plants.*By 2013, PWSD plans to design and construct a new WTP at 15th Avenue and Dobbins Road. PWSD will also reconstruct, rehabilitate, and/or optimize processes at four WTPs. Security will be upgraded at CCWRP, which will also be rehabilitated to some extent.

*Transmission and distribution.*The city will replace, rehabilitate, and/or relocate a number of water mains and transmission lines. New mains will also be constructed in growth areas, as well as in the Camelback East residential corridor.

*Customer services and metering.*The city plans to upgrade its current Customer Information System, and will acquire and install software to automate meter reading. Finally, new service meters will be installed and plumbing connections will be constructed for alley service relocations.

B.4 Utility Planning and Management: Issues and Approaches

PWSD is currently working to address future water supply reliability within the context of climate change and other uncertainties. Key decisions and investments PWSD is making and/or faces in the nearterm include the development of a new drought and shortage management plan and planning for the development of additional long-term supply sources. In terms of both drought and supply planning, the city's the core focus is adequacy and affordability of "shortage insurance" to maintain lifestyles and the economy.

B.4.1 Addressing Key Uncertainties

As noted in previous sections, in addition to climate change, there are a number of uncertainties that the city has begun to plan for in terms of drought management and long-term supply planning. These uncertainties include the timing and length of reduced inflows from SRP or CAP, growth and development in Phoenix and the upper Colorado River basin, institutional decisions (e.g., how the seven Colorado River Basin states, and groups of water users within Arizona, will respond to system shortages), environmental mandates, water quality impacts, long-term groundwater availability, water conservation potential, economic impacts, and the ability to fund acquisitions and infrastructure (PWSD, 2006, 2010).

To account for these uncertainties, Phoenix has developed a comprehensive planning framework that includes the development of various planning scenarios. The planning scenarios account for differences and uncertainties associated with (1) the availability of supplies (based on climate and other factors), (2) future demand (including differences in growth and development patterns), and (3) conservation levels. For the development of the 2005 Water Resources Plan, 144 different scenarios were developed based on these different factors.

For the 2005 water resources planning effort, analysis of the various scenarios through 2030 allowed the city to evaluate the likelihood of different factors that would contribute to future water supply shortages, as well as the range of potential future shortages. As discussed in the following sections, more current planning efforts have begun to include climate change-related impacts.

B.4.2 Drought Management and Shortage Planning

Phoenix is currently in the process of revising its shortage/drought management plan, which, given the city's relatively ample supply, will not look like a typical water utility drought plan (i.e., which typically outline stages of drought and accompanying drought responses, such as levels of water use restrictions). The plan will be focused more on an adaptive strategy ofdrought planning over time and will incorporate the development of alternative supply options. For example, the city will outline specific actions that will need to be taken over a

10-year time frame in advance of an expected shortage. Supply augmentation and planning will be initiated as a first step, with demand-side management strategies being implemented closer to the time of the expected shortage. Figure B.2 depicts this adaptive strategy.

Figure B.2.Phoenix water shortage planning framework.

Source: PWSD, 2010.

Demand-side options are an important component of the city's drought management and supply planning framework. The city's demand management toolbox includes the following strategies (PWSD, 2010):

- Trend research and audits
- System loss management (i.e., reducing unaccounted-for water)
- Direct and leveraged assistance/outreach
- Support for technological advancements
- Support for improved standards
- Banking of conservation savings
- Structured curtailment planning
- Alternative rate and fee structures

The city's supply toolbox includes groundwater (local and imported), reclaimed water (direct, stored and recovered), additional surface water supplies (direct, stored and recovered), desalination, water exchanges, and the Arizona Water Bank. The following sections provide additional detail on these alternative options

B.4.3 Future Supply Options

Phoenix has identified several additional water sources for potential future development. These are described here and summarized in Table B.2.

Table B.2. Summary of the Different Water Supply Options Identified in Figure B.2, Including Available Volume, Feasibility, Cost, and LeadTime Necessary to Implement

Supply Source	Volume (up to)	Relative Certainty	Cost to Implement	Lead Time
Local groundwater	65,000	High	High	2–10 years
Exchange groundwater	?	High	Low–med	1–2 years
McMullen Valley groundwater	30,000	Low	High	5–10 years
Reclaimed—stored/recovered	?	Med	High	2–5 years
Reclaimed—direct nonpotable	20,000	Med	High	2–5 years
Reclaimed—direct potable	100,000	Med	High	10–15 years
CAP subcontract (ASLD)	8000	Med	Low	1–10 years
CAP Indian lease (WMA)	2000	Med	Med	8 years
AZ Water Bank	24,000	High	Med	5–0 years
Excess CAP—stored/recovered	20,000	High	High	2–10 years
Demand efficiency(10%)	30,000	Med	Low	5–10 years
Demand curtailment (15%)	45,000	Med	Med	5–10 years

Note: ASLD =Arizona State Land Department.

*Additional local groundwater.*The city is considering expanding local well production capacity to reduce drought impacts and to provide operational flexibility and efficiency. An expanded well network could also play an important role in recovering stored water credits (i.e., CAP, reclaimed water, and other supplies that have been recharged into the aquifer for later use). To help ensure the availability of good-quality groundwater, Phoenix plans to work closely with ADEQ and EPA on cleanup strategies for the central Phoenix contamination issues.

*McMullen Valley groundwater.*In 1986, the city acquired almost 14,000 acres of agricultural lands in the McMullen Valley, approximately 80 miles west of Phoenix. Much of this land continues to be farmed under lease arrangements. The city's intent is to retire these farmlands and transport the groundwater to the municipal water service area. This imported groundwater would be conveyed via pipeline to the CAP canal. The CAP Board has approved an interim set-aside of 38,000 AF per year of excess CAP canal capacity for transport of McMullen Valley groundwater to Phoenix.

*Reclaimed water.*Despite the substantial use of Phoenix's reclaimed water for turf irrigation, cooling, and agricultural purposes, additional reclaimed water is available for reuse. The volume produced at Phoenix's plants periodically exceeds demand (especially during winter months). Some of the unused water is used to recharge local aquifers;however, a large percentage is discharged to the Salt River. Studies are underway to determine the feasibility of storing some of the unused water underground along the Agua Fria River from Bell Road to Indian School Road. The stored water could ultimately be recovered from Phoenix wells to meet both nonpotable and potable customer demands.

The city is also considering expansion of reclaimed water recharge and recovery facilities in north Phoenix. In addition, the city is evaluating the use of reclaimed water as a source of potable supply. It is not yet known how PWSD's customer base will respond to this idea. Further, though a city ordinance requires the use of nonpotable water by large turf facilities where practical, the high costs of developing dedicated distribution systems to serve customers in the Phoenix service area remains a major obstacle to direct utilization of the supply.

*Additional CAP supplies.*There are currently 12,000 AF of CAP supplies, which were allocated to the ASLD, which are being held in reserve for state trust lands in Phoenix, north of JomaxRoad. Based on a 1986 commitment from the ASLD, this allocation will be transferred to Phoenix as the area north of Jomax Road is developed.

In addition, agricultural priority CAP water may be available to the city via a state-managed process that will allocate between 75,000 and 90,000 AF to interested parties over three decades (supposedly beginning in 2010). Presuming Phoenix is successful in obtaining a portion of this supply, a strategy to firm this supply will be needed to offset years where this lower-priority water may be reduced because of Colorado River shortages.

*Brackish groundwater.*Desalination of brackish groundwater has been considered as one opportunity to meet the increasing water demands of growing West Valley communities. Areas to the southwest of Phoenix are underlain by substantial volumes of relatively shallow brackish groundwater with high TDS levels of more than 2500 mg/L. Studies are currently underway to quantify the sustainable quantity available and to assess the usability of these brackish supplies by Phoenix and other West Valley communities. The major challenge associated with desalination involves disposal of the brine concentrate byproduct.

B.5 Climate Change Impacts on Phoenix

Climate change may impact Phoenix in a number of important ways. Changing precipitation patterns and higher temperatures may have significant effects on water supply sources and demand. Higher temperatures and increasing flooding events could affect water quality in important ways. More frequent and more severe droughts may have important effects on water supply and drought management operations and capital investments. Increasing frequency and severity of flooding events could affect water supply and treatment infrastructure as well.

B.5.1 Regional Climate Scenarios

Generally speaking, the southwestern United States faces some of the most dramatic projected impacts from climate change in the country. The Southwest's relatively arid continental climate leads to hightemperatures, inconsistent seasonal precipitation, and snowmelt-dominated watersheds. According to the USGCRP, the average temperature of the Southwest has already increased about 1.5 °F over the 1960–1979 baseline. Furthermore, temperatures in the region are projected to rise approximately 4–10 °F by the end of the century, significantly more than the global average (Karl et al., 2009). A recent study by Seager et al. (2007) found a broad consensus among projections from 19 GCMs used in the Fourth Assessment of IPCC that the Southwest will dry significantly in the 21st century.

Droughts are perhaps the most important facet of the climate of the Southwest. In conjunction with warmer temperatures, earlier snowmelt, and projections of decreased precipitation, the

possibility of more frequent or more severe droughts is a critical issue for the Southwest. Despite many uncertainties, most projections point to an increasing probability of drought for the region and a substantially drier future (e.g., Meehl et al., 2007a; Seager et al., 2007; Karl et al., 2009).

Physically speaking, a warmer atmosphere can hold more water vapor, thus intensifying the water cycle. This is one of the physical reasons to expect a warmer future to increase droughts in the Southwest. More moisture in the atmosphere, however, also means that when it does rain, storms are likely to be more intense and involve more precipitation, increasing the likelihood and severity of floods. Winter precipitation in Arizona has already exhibited a trend toward both more frequent extreme dry and extreme wet conditions (Goodrich and Ellis, 2008).

B.5.2 Impacts of Climate Change on the City of Phoenix Water Services Department

The main impacts of climate change on Phoenix will be on water supply and availability relative to demand, water quality of source and receiving waters, infrastructure integrity and reliability, and regional population and economic trends.

B.5.2.1 Water Supply/Demand and Climate Change

In essence, there are three main issues important to understanding the impact of climate change on water supply and demand in Phoenix: (1) the impact of climate change on water supplies from the Colorado River basin, (2) the impact of climate change on water supplies from the Salt and Verde River watersheds, and (3) the impact of climate change on water demands in the Phoenix water service area. A fourth item also discussed in this section is paleoclimate studies relevant to Phoenix water supplies. Technically speaking, paleoclimate studies do not provide information about climate change;however, they do provide a better understanding of regional climate variability than simply relying on the observed record. Such paleoclimate studies have been used by PWSD and merit mention alongside projections of future climate.

B.5.2.2 Colorado River Basin

Because almost half of Phoenix's water supply comes from the CAP, which transports Colorado River water to Phoenix, it is important to consider not just local climate projections for Phoenix, but the impact of climate change on the entire Colorado River basin.

State-of-the-art knowledge of the Colorado River basin suggests climate-change-induced reductions in average annual flow by10% to 20% by about 2050 (Barsugli and Lukas, 2010). Until recently, projections for climate change impacts on Colorado River flows ranged from a 45% reduction by 2050 (Hoerling and Eischeid, 2007) to only a 5% reduction by 2050 (Christensen and Lettenmaier, 2007). Because of the wide range of these estimates, a group of scientists from universities, NOAA, and USBR engaged in an assessment project called "Reconciling projections of future Colorado River streamflow." This project is still in process, but it has developed some agreement on key issues that previously led to widely varying estimates as well as key research needs. Consequently, current estimates of Colorado River flow decline range from approximately 5% to 20% by 2050 (Hoerling et al., 2009).

A series of studies have also been conducted on translating changes in Colorado River flow into changes in Colorado River water storage and availability in Lake Powell and Lake Mead. The first and most controversial of these articles was titled "When Will Lake Mead Go Dry?"(Barnett and Pierce, 2008). This paper concluded that under climate change, Lake Mead and Lake Powell would have a 50% chance of going dry by 2021. A series of subsequent articles challenged the assumptions of this article and generated a thoughtful discussion about what 10% or 20% changes in Colorado River flow would mean for Colorado River water supplies (Barnett and Pierce, 2009; Barsugli et al., 2009; Rajagopalan et al., 2009).

Barsugli et al. (2009) concluded that Lake Mead had only a 20% chance of going dry by 2021, and the 50% chance did not occur until the 2035–2047 timeframe under a 20% reduction in flow. However, Barsugli et al. (2009) still concluded that projected changes in flow because of climate change, in conjunction with projected increases in demand, would begin "dragging the system toward increasingly lower reservoir storage and higher risk of shortages" in the late 2020s (Barsugli and Lukas, 2010). The Rajagopalan et al. (2009) study found similarly lower, but still significant risks of drying by using multiple policy scenarios to mitigate risk of drying, better representing uncertainty in future demand, and accounting for the entire storage of the Colorado River rather than just Lake Powell and Lake Mead. In response to these papers, Barnett and Pierce (2009) revised their assumptions to nearly match those of Barsugli et al. (2009) and Rajagopalan et al. (2009).

The Barnett and Pierce (2009) study suggested that Lower Basin deliveries of Colorado River water faced significant risk. They concluded that average delivery shortfall to the Lower Basin under a 20% reduction in flow by 2050 was 2.2 million AF (MAF). This assumed projected deliveries of 8.23 MAF to the Lower Basin minus shared shortages per the interim shortage guidelines adopted by Colorado River Compact signatory states in 2007. According to Barsugli and Lukas (2010), although each of these studies differs in some details, they all point toward a common broad-brush conclusion:Consumption and other depletions are approaching average annual inflow, narrowing the margin of error for managing Colorado River water. Add potential flow reductions because of climate change on top of that, and the risk of delivery shortages and/or reservoir depletions increases dramatically by 2050.

B.5.2.3 Salt and Verde River Watersheds

PWSD has worked extensively with the University of Arizona and NOAA's Regional Integrated Sciences and Assessments program—CLIMAS—on studying the impact of climate change onPhoenix's SRP. Because these studies have not been published and are not publicly available, Stratus Consulting conducted its own analysis of climate change impacts on the Salt and Verde River watersheds—two using bias-corrected and spatially downscaled projections separately for the Salt and Verde River watersheds and one using GCM projections for the combined Salt and Verde River watersheds.

Stratus Consulting used the bias-corrected and spatially downscaled climate projections derived from CMIP3 data and availableat http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/, described by Maurer et al. (2007), to determine projected change in temperature and precipitation for the Salt and Verde River watersheds. Stratus Consulting accessed projections of monthly absolute temperature and precipitation rates for three selected time periods: 1970–1999, 2050–2069, and 2080–2099. The projections were derived from the full complement of all available data in the Maurer dataset, including all 112 GCM/scenario/run combinations.

For the Salt River watershed, the data were delivered as a spatial average of 152 1/8th° grid cells (approximately 8 miles across each) for a square block that encompasses the Salt River watershed, as illustrated in Figure B.3. A similar square block encompassing the Verde River watershed (see Figure B.3) was used to spatially average the data over 224 1/8th° grid cells. We then further processed thosedata both for monthly averages (see Tables B.3 and B.5) and annual averages (see Tables B.4 and B.6) for all three time periods. To determine changes over time instead of absolute values, we subtracted the 1970–1999 values from the 2050–2069 and 2080–2099 projections, expressed as degree change over baseline for temperature and percent change over baseline for precipitation.

The annual average temperature results in Tables B.4 and B.6 indicate that the Salt and Verde River watersheds are projected to warm approximately 2–3 °F by 2060 and approximately 2.5–4.5 °F by 2090. These ranges indicate the uncertainty associated with future GHG concentrations because of divergent future global socioeconomic development patterns. The monthly temperature results in Tables B.3 and B.5, however, indicate that under all three scenarios, temperatures risemore in the summer months than in the winter months for both 2060 and 2090. Despite all of the inherent uncertainties in climate projections, the consistency of warming across all scenarios, all months, and all future time periods lends weight to the conclusion that a warmer future is in store for the Salt and Verde River watersheds. Agreement among model averaged scenarios on the seasonal difference in warming is compelling, but further analysis ofintermodel agreement on this seasonal change is warranted before any firm conclusions are drawn.

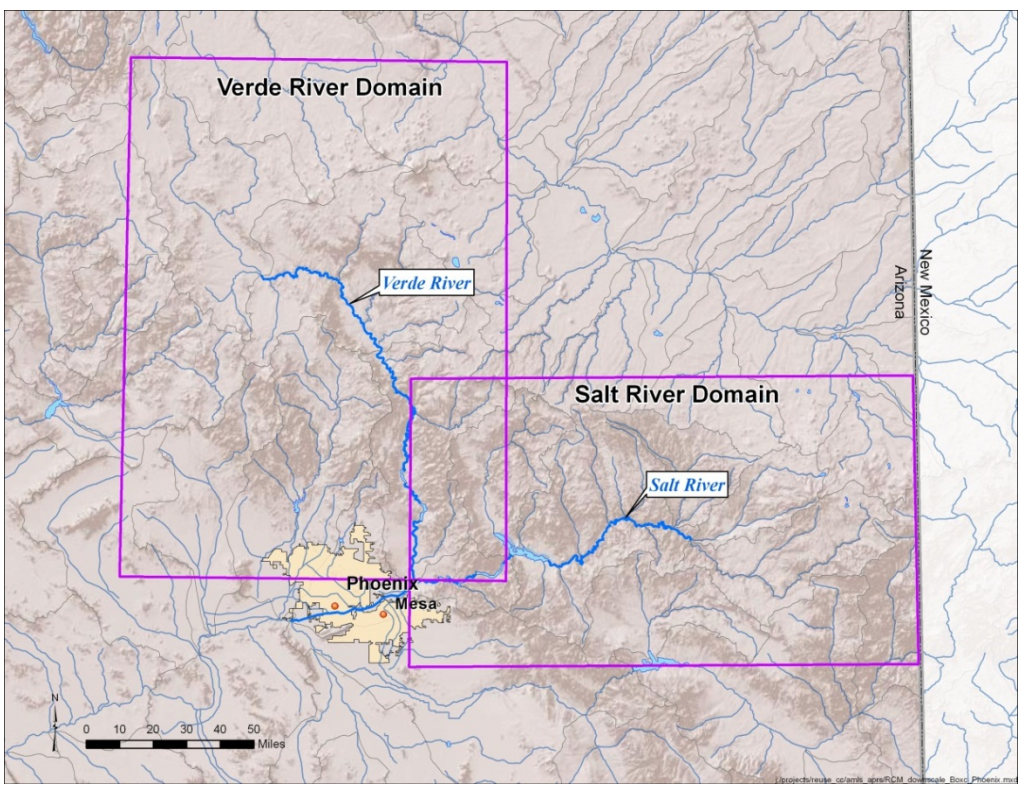

Figure B.3. The spatial domains for analysis of climate change in the Salt and Verde Rivers using the Maurer dataset.

Table B.3. Projected Monthly Changes for the Salt River Watershed (as Derived from the Maurer Dataset)

	Change from 1970 to 1999 for Scenario B1 (precip.: %; temp.: °F)				Change from 1970 to 1999 for Scenario A1B (precip.: %; temp.: °F)				Change from 1970 to 1999 for Scenario A2 (precip.: %; temp.: °F)			
	2050–2069		2080–2099		2050–2069		2080–2099		2050–2069		2080–2099	
	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.
Jan	-5.45	2.72	-1.26	3.62	-5.99	3.80	-9.04	5.35	-1.79	3.58	-5.90	6.35
Feb	-10.57	2.86	-4.58	3.96	-6.17	3.74	-12.50	5.49	-9.08	3.89	-15.41	6.73
Mar	-9.45	3.08	-13.40	3.98	-19.37	4.30	-15.62	5.87	-17.18	4.12	-24.44	6.95
Apr	-26.41	3.67	-24.94	4.52	-30.91	4.91	-31.84	6.32	-33.00	4.91	-50.37	8.03
May	-4.21	3.76	-13.09	4.75	-18.55	5.15	-27.16	6.93	-30.34	5.24	-42.20	8.68
Jun	-9.39	4.01	-3.42	4.88	-4.96	5.56	-6.02	7.20	-8.92	5.56	-17.03	8.77
Jul	4.57	3.98	8.38	4.57	3.04	5.44	7.28	6.88	0.37	5.45	6.32	8.42
Aug	1.79	4.12	3.39	4.93	3.02	5.56	-1.77	7.49	-6.16	5.67	-2.61	9.12
Sep	1.06	4.37	3.33	5.35	8.57	5.71	-0.16	7.99	-7.20	5.92	1.52	9.61
Oct	1.68	4.07	-3.15	5.13	1.18	5.71	6.66	7.42	0.38	5.51	5.03	9.25
Nov	-7.76	3.33	-6.76	4.36	-7.49	4.70	-12.55	6.28	-9.29	4.54	-13.97	7.74
Dec	-1.43	2.72	-10.33	3.56	-6.02	3.82	-6.90	5.22	-7.37	3.80	-12.45	6.57

Table B.4. Projected Annual Average Changes for the Salt River Watershed (as Derived from the Maurer Dataset)

	Change from 1970 to 1999 (precip.: %; temp.: °F)			
	2050–2069		2080–2099	
Scenario	Precip.	Temp.	Precip.	Temp.
B1	-3.60	3.56	-3.20	4.46
A1B	-4.46	4.86	-6.25	6.53
A2	-7.94	4.84	-9.33	8.01

Table B.5. Projected Monthly Changes for the Verde River Watershed (as Derived from the MaurerDataset)

	Change from 1970 to 1999 for Scenario B1 (precip.: %; temp.: °F)				Change from 1970 to 1999 for Scenario A1B (precip.: %; temp.: °F)				Change from 1970 to 1999 for Scenario A2 (precip.: %; temp.: °F)			
	2050–2069		2080–2099		2050–2069		2080–2099		2050–2069		2080–2099	
	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.
Jan	-2.92	2.75	2.03	3.67	-2.23	3.85	-4.55	5.36	2.76	3.56	-1.98	6.34
Feb	-8.17	2.92	-1.65	4.01	-3.65	3.74	-6.96	5.49	-5.19	3.85	-10.35	6.68
Mar	-6.18	3.02	-11.81	3.92	-17.49	4.21	-13.32	5.76	-13.62	4.0	-22.32	6.75
Apr	-27.49	3.60	-23.05	4.43	-29.97	4.81	-29.23	6.12	-32.43	4.70	-49.22	7.78
May	-11.77	3.78	-19.80	4.73	-24.70	5.09	-31.73	6.79	-34.80	5.17	-48.25	8.50
Jun	-12.01	4.05	-6.27	4.90	-13.36	5.67	-14.95	7.25	-16.33	5.69	-25.76	8.68
Jul	6.93	4.14	11.68	4.75	4.55	5.62	12.13	7.07	3.68	5.63	11.09	8.69
Aug	0.01	4.25	5.06	5.04	4.28	5.76	-2.91	7.65	-4.27	5.80	-0.16	9.23
Sep	2.73	4.45	6.47	5.44	11.58	5.81	1.72	8.15	-6.85	6.01	4.45	9.77
Oct	-1.75	4.07	-4.17	5.04	0.43	5.67	9.08	7.33	0.31	5.45	6.10	9.16
Nov	-8.72	3.28	-8.27	4.30	-6.72	4.63	-10.95	6.14	-7.80	4.46	-13.42	7.58
Dec	-0.78	2.68	-10.33	3.56	-7.08	3.76	-7.16	5.18	-6.43	3.74	-11.99	6.53

Table B.6. Projected Annual Average Changes for the Verde River Watershed (as Derived from the Maurer Dataset)

	Change from 1970 to 1999 (precip.: %; temp.: °F)			
	2050–2069		2080–2099	
Scenario	Precip.	Temp.	Precip.	Temp.
B1	-3.67	3.58	-2.28	4.48
A1B	-3.97	4.90	-5.11	6.52
A2	-6.62	4.84	-8.16	7.97

The results in Tables B.4 and B.6 show annually averaged precipitation decreases in the Salt and Verde River watersheds across all three scenarios for both 2060 and 2090. Scenario B1 indicates precipitation decreases on the order of 3–4%; scenario A1B indicates precipitation decreases on the order of 4–6%;and scenario A2 indicates precipitation decreases on the order of 7–9%. The monthly precipitation results in Tables B.3 and B.5, however, indicate that under all three scenarios precipitation is projected to decrease in November through June, with those decreases especially pronounced (upward of 25–50%) during the spring months. The months of July through October, however, indicate small precipitation increases, although these increases are not consistent across all months and scenarios. It should be noted that changes in precipitation are much more uncertain than changes in temperature and are not uniform in directionality (i.e., some models indicate a precipitation increase and others a decrease). Thus, it is even more important to consider the range of projections among the models through statistics such as standard deviations across model averaged scenarios. Again, agreement among model averaged scenarios on the seasonal difference in precipitation is compelling, but further analysis ofintermodel agreement on this seasonal change is warranted before any firm conclusions are drawn.

For comparison with the Maurer results in Tables B.3–B.6, Stratus Consulting also conducted an analysis of GCM data using the software package MAGICC-SCENGEN. The results of 16 GCMs over a geographic area encompassing the majority of the combined Salt and Verde River Watersheds was analyzed. This area was composed of two 2.5° grid boxes ranging from 32.5° to 35° in latitude and -112.5° to -107.5° in longitude. The results from this analysis are shown in Table B.7.

Table B.7. Projected Monthly and Average Annual Temperature and Precipitation for Combined Salt and Verde River Watersheds (as Derived from MAGICC-SCENGEN)

	Change from 1990 for Scenario A1B (precip.: %; temp.: °F)			
	2060		2090	
Month	**Precip.**	**Temp.**	**Precip.**	**Temp.**
Jan	0.21	4.34	-0.60	6.06
Feb	4.90	5.06	6.32	7.33
Mar	1.28	N/A[a]	4.03	N/A[a]
Apr	-19.18	5.23	-22.80	7.54
May	-14.06	6.24	-33.29	8.48
Jun	-30.51	6.62	-43.29	8.89
Jul	-24.88	6.31	-34.99	8.93
Aug	-2.70	5.79	-14.41	7.68
Sep	31.61	6.03	48.02	8.21
Oct	3.68	6.00	2.59	8.39
Nov	-25.30	5.30	-39.18	7.51
Dec	-14.15	4.96	-21.12	7.05
Ann	-5.39	5.57	-7.57	7.78

[a]A programming error occurred in processing projections for March precipitation.

The MAGICC-SCENGEN results indicate that the Salt and Verde River watersheds are projected to experience a decline in average annual precipitation and higher temperatures. Eleven of 16 models projected a precipitation decrease in 2060, and 12of 16 models projected a precipitation decrease in 2090. The annual average temperature and precipitation results from both bias-corrected and spatially downscaled Maurer analyses and the MAGICC-SCENGEN analysis are roughly consistent, as shown in Table B.8.

There are, however, a number of inconsistencies between the MAGICC-SCENGEN and Maurer projections. For example, although the average annual precipitation results are consistent, the MAGICC-SCENGEN data indicates sizable precipitation declines in July, whereas the Maurer results indicated modest precipitation increases for July. This difference in the seasonality of precipitation merits further investigation, as summer monsoon storms are a significant source of precipitation for the Salt and Verde River watersheds. Also, the projected temperature increases are slightly higher for the MAGICC-SCENGEN projections than for the Maurer projections—although the bias correction of the Maurer dataset is certainly responsible for some of this difference.

B.5.2.4 Water Demand in the Phoenix Water Service Area

Water demands in the Phoenix water service area is the other side of the water balance equation. Increased temperatures and reduced precipitation could cause demands to rise and effect the ability of PWSD to provide adequate water to meet demands. A large proportion of Phoenix water demand is for outdoor landscape irrigation use and swimming pools. This comprises some 60% to 75% of all water demand depending upon municipality (PWSD, 2006; Balling et al., 2008). In theory, such a large proportion of outdoor water use should make Phoenix more vulnerable to demand variations that are due to climate.

Utility personnel that have examined the difference in customer demands between hot and dry versus cold and wet summers, however, discovered that some of the most dramatic year-to-year variations only increased water demands by some 3% (Steve Rossi, City of Phoenix Water Services Department, personal communication, October 5, 2010). Furthermore, other peer reviewed literature has come to a similar conclusion that structural factors, prevailing water use practices, and low water prices all contribute to the relative insensitivity of Phoenix urban water use to variations in climate (Balling and Gober, 2007; Balling et al., 2008). These studies also indicate that some neighborhoods are more climate sensitive than others. But for the purposes of overall demand, the variation brought about by climate change appears to be relatively minor compared to changes in water supply.

Table B.8. Comparison of Maurer and MAGICC-SCENGEN Annual Average Results for Scenario A1B (precip: %; temp: °F)

	2060		2090	
	Precip.	Temp.	Precip.	Temp.
Maurer (Salt)	-4.46	4.86	-6.25	6.53
Maurer (Verde)	-3.97	4.9	-5.11	6.52
MAGICC-SCENGEN	-5.39	5.57	-7.57	7.78

Note: Despite slightly different geographic and temporal scales/baselines between Maurer and MAGICC-SCENGEN, the results are roughly comparable.

B.5.2.5 Paleoclimate Studies for the Colorado River

A number of recent paleoclimate studies have provided insight into the significant differences between the observed climate record over the 20th century and longer-term trends over the past 500–1200 years. For example, the observed average inflow into Lake Powell from 1905 to 2005 was 15.0 MAF/yr. However, a number of tree ring studies indicate that the twentieth century has been anomalously wet compared to the past 500–1200 years. The average of three recent paleoclimate studies indicates a long-term average inflow into Lake Powell of 14.6 MAF (Woodhouse et al., 2006; Meko et al., 2007; Gangopadhyay et al., 2009). The average of all paleoclimate studies of the Colorado River is 14.1 MAF (Barsugli and Lukas, 2010). In addition to suggesting that the observed record overestimates the average inflow into Lake Powell, these paleoclimate studies also indicate that the Colorado River basin has experienced longer and more frequent droughts than experienced over the 20th century.

According to the tree-ring reconstruction by Woodhouse et al. (2006), Colorado River flows at Lee's Ferry historically suffered from droughts longer and more severe than the 1999–2004 drought event. Although the 1999–2004 event was likely the most severe and prolonged in the observed record, it is not without precedent in the tree ring record. For example, the average annual reconstructed flow for the period 1844–1848 was lower than 1999–2004 average annual observed flow. Furthermore, there are several periods with longer-duration droughts, including a 6-year drought from 1663 to 1668, an 8-year drought from 1776 to 1783, and an 11-year drought from 1873 to 1883. Overall, this indicates that severe and sustained droughts are a defining feature of the Colorado River basin.

Meko et al. (2007) used remnant preserved wood to extend their tree-ring reconstruction of Colorado River flows from A.D. 762 to 2005. Gangopadhyay et al. (2009) used a nonparametric method to analyze reconstructed Colorado River flows from A.D. 1400 to 2005. These and other studies have extended the record and added methodological nuances to tree ring reconstructions. However, the main conclusions hold across all of these studies. Namely, average annual flow over the long-term record is much lowerthan average annual flow observed in the short-term record (including assumptions made to allocate Colorado River water in the Colorado River Compact). Furthermore, severe droughts such asthe early twenty-first century event are relatively common over the long-term reconstructed record, even though it was anomalous for the observed record.

B.5.2.6 Regional Population and Climate Change

The Phoenix Water Supply District has historically planned for significant growth because of the large population growth observed from 1990 through 2006 (PWSD, 2006; U.S. Census, 2010) and urban growth projected to increase by 66% by 2030 (Maricopa Association of Governments, 2007). Subsequently, the housing market and commercial real estate collapse haveled to at least two years of stagnant population growth or perhaps a small population decline (PR Newswire, 2009). Because of this population resilience in the face of a largenumber of foreclosures and job losses, a report by the ULI (2009) suggests that the future Phoenix may not be fueled by rapid population growth, but rather by providing opportunities to the many jobless whohave remained in the area.

Despite the difficulty of projecting population growth in the current economic situation, climate changes could act as a driver of regional population trends. Although very little information currently exists on how climate changes could affect in- and out-migration from population centers, temperature increases on the order of 5 °F by 2060 and 7–8 °F by 2090

could affect the desirability of living in Phoenix and could conceivably lead to a tempering of population growth or even out-migration.

Regardless, in the near term, population increases are likely, and the majority of increased water demand that is due to such population increases is likely to come from outdoor water use for landscaping and pools. According to the PWSD, it is currently approaching behavioral, technological, and other limits to increases in conservation, and water demand that is due to population growth will soon overtake conservation improvements to yield net water demand increases (Steve Rossi, City of Phoenix Water Services Department, personal communication, October 7, 2010).

B.6 Reuse as a Climate Change Adaptation

Water reuse can enhance the flexibility of a water system by effectively reducing the demand for or increasing the supply of potable water. Demand for potable water can be reduced by providing reuse water for nonpotable applications such as turf irrigation that would otherwise draw upon the potable supply. The supply of potable water can be enhanced through indirect potable reuse—for example, by recharging aquifers.

B.6.1 Actual and Potential Reuse in Phoenix

PWSD already highly treats and reuses more than 90% of itswastewater. This was originally done to provide reuse water for large turf facilities in northeast Phoenix. It was later extended to provide reuse water for irrigation in the RID, for BIC, and for the Palo Verde Nuclear Generating Station.

When the supply of reclaimed water exceeds demand because of seasonal variations in demand from turf facilities and irrigation, unused water is stored underground at the RID Groundwater Savings Facility. The city has stored approximately 100,000 AF of reclaimed water to date. The city has recognized the importance of reuse water as a supply source and has committed to full (100%) utilization of reuse water, including the possibility of constructing a second water reclamation plant in north Phoenix.

Phoenix has taken a forward-leaning approach towater reuse. As a consequence, there is a wealth of experience in water reuse in the area and close to full utilization of wastewater for reuse applications. Further opportunities for water reuse may be constrained by the legal classification of stored reuse water as effluent and the economic cost of providing a parallel delivery infrastructure for reuse water.

Appendix C

Case Study: Inland Empire Utilities Agency

C.1 Overview of the Inland Empire Utilities Agency

This IEUA case study examines the current hydrological and institutional challenges and issues faced by IEUA in managing the uncertainties associated with climate change. In addition, this study specifically examines the role water reuse plays in addressing uncertainties of all kinds.

This section provides a brief overview of the services provided by IEUA, its water supply sources, and its current water reuse program.

C.1.1 Services Provided

IEUA is a wholesale distributor of water and recycled water and also provides regional wastewater treatment services for a 242-square mile area of western San Bernardino County that overlies the Chino Basin (Figure C.1; IEUA, 2010). In 2007, IEUA had an estimated service population of approximately 800,000. IEUA serves eight water retail agencies: the cities of Chino, Chino Hills, Ontario, and Upland; the Cucamonga Valley and Monte Vista water districts; and the Fontana and San Antonio water companies.

IEUA closely coordinates its water resource management program with the Chino Basin Watermaster, the San Bernardino County Flood Control District, the Chino Basin Water Conservation District, and local water and sewer retail agencies. IEUA is a member of the MWD.

IEUA also coordinates wastewater treatment services with seven wastewater contracting agencies. Industrial and municipal wastewater aremanaged through a network of regional wastewater sewer interceptors and two NRW sewer pipeline systems; treatment at five regional treatment plants; biosolids management; and other related wastewater utility services. IEUA has a total treatment capacity of 60 mgd. The agency also owns a co-composting facility and has a managing interest in the Chino 1 and 2 desalters.

In its 2008/2009 Annual Report, IEUA President Richard Atwater stated, “IEUA views its business as manufacturing three products: high-quality recycled water to help drought-proof our service area, converting high-quality compost to ensure healthy solids, and renewable energy through methane gas and solar generation facilities.”

C.1.2 Water Supply Sources

In 2007, IEUA’s annual water demands averaged about 250,000 AFY. Approximately 25% of the water supply is purchased from MWD and provided through the California SWP, 65% comes from groundwater, 7% from local stream flow, and the remaining 3% is from recycled water (IEUA, 2007).

Figure C.1. IEUA location map.

Source: IEUA, 2010.

C.1.3 Current Water Reuse Program

IEUA has been in the forefront in itsunderstanding of the interrelationship among water supply, water treatment, and the related infrastructure. Itsfour wastewater facilities currently produce about 60 mgd of recycled water. This water is currently used for nonpotable uses, including irrigation and industrial use, and also for recharge of the Chino Basin.

In 2000, IEUA recognized that recycled water is the only source of new water available for the region. In the last 10 years IEUA and local water providers have invested in new water infrastructure, including 75 miles of pipeline for distribution of recycled water. Plans are underway for an additional $40 million investment in new recycled water systems.

IEUA believes that recycled water provides a clean, safe, new source of water that will reduce reliance on expensive imported water, save money (and water!), and assist in drought-proofing the region. Additional details of the IEUA Water Reuse program are provided in Section C.2.

C.2 Regional Setting

During the past two decades, the IEUA service area has consistently been one of the fastest-growing regions in the nation. With this growth comes numerous challenges. The local water supply consists primarily of an overdrawn salt-laden aquifer (the Chino Basin). In addition, the only obvious way to meet the growing demand for water is to purchase expensive imported water.

IEUA met these challenges by developing an innovative plan that manages the Chino Basin aquifer in a way that both increases supplies and improves water quality. IEUA accomplished this, in part, by developing legal agreements that benefit the entire region and by developing a new source of water rarely considered just 20 years ago—recycled water.

In this section, we review how IEUA maximized its local water supply by actively managing the Chino Groundwater Basin.

C.2.1 Land Use and Population

During the 19thand early 20th centuries, the IEUA region was a major agricultural center that included citrus groves, dairy farms, and wineries. Today, the Inland Empire is one of the fastest-growing regions in the nation. Between 2000 and 2005, the area's population grew from about 700,000 to about 800,000. As a result, there has been an unprecedented conversion of agricultural lands to residential, commercial, and industrial uses (IEUA,2006).

C.2.2 Current Water Supply Strategy

As a Basin-wide water broker, IEUA manages four types of water supply—groundwater, imported water, surface water, and recycled water—with the Chino Groundwater Basin being the largest single source. Figure C.2 provides a detailed outline of the amount of water supplied from each source for the past 10 years. With its history of agricultural overuse and pollution (primarily nitrogen in the form of salts), the Chino Basin was considered overtaxed and compromised as early as 1940.

Imported water supplyfrom northern California isthe most expensive source of water for IEUA customers. These sources are becoming increasingly unreliable, particularly underdrought conditions. In addition, recent court orders have significantly limited the amount of water that can be extracted from northern California's Bay-Delta for transmission to MWD via the SWP (because of environmental concerns associated with the impact of the extractions on special-status fish species).

To limit the need for expensive imported MWD waters and create supply flexibility both now and in the future, IEUA developed a strategy that includes groundwater recharge, storing extra water during wet years, conservation, groundwater desalting, and recycled water.

C.2.2.1 Groundwater Recharge Regime Program

The Chino groundwater basin is the largest groundwater basin in southern California, currently containing 5,000,000 AF of water, with an additional 1,000,000 AF of unused storage capacity. Water rights within the Basin have been adjudicated, and the average safe yield of the Basin is 140,000 AFY. (A description of the adjudication process is provided in Section C.3.)

Water Source	Fiscal Year Ending June 30					
	2000	2001	2002	2003	2004	2005
Chino Basin Groundwater	89,879	80,871	85,806	92,501	89,103	84,551
Other Basin Groundwater	56,175	45,991	39,964	43,024	42,377	36,198
Surface Water	9,924	13,543	8,903	9,554	9,058	18,060
Imported Water	60,892	57,545	68,560	61,027	80,170	67,694
Recycled Water[a]	6,030	3,797	4,442	4,498	5,408	5,396
Desalter	0	3,213	4,519	6,499	4,696	3,904
Agricultural groundwater use	30,993	27,397	27,878	28,429	31,790	25,593
Total	**253,893**	**232,357**	**240,072**	**245,532**	**262,602**	**241,396**

Water Source	Fiscal Year Ending June 30				
	2006	2007	2008	2009	2010
Chino Basin Groundwater	77,195	90,032	87,908	66,351	68,277
Other Basin Groundwater	48,780	53,830	43,401	46,418	41,724
Surface Water	18,756	21,184	18,411	16,767	25,578
Imported Water	68,456	69,453	68,951	78,872	54,934
Recycled Water[a]	8,847	13,029	13,493	13,360	17,298
Desalter	6,449	12,904	15,301	14,810	14,810
Agricultural groundwater use	24,655	24,690	20,211	21,000	21,043
Total	**253,138**	**285,122**	**267,676**	**257,578**	**243,664**

[a]Recycled Water use by eight retail agencies and IEUA

Sources: Chino Basin Watermaster assessment table, WFA water deliveries, and retail agency records.

Figure C.2. Total water production by source within IEUA service area (AFY).

As a result of historical agricultural use, the high TDS loads from past use of imported Colorado River waters, and the influx of dairies into the lower Chino Basin region from Los Angeles County, salt has built up (mostly in the form of nitrates) in the Basin. Some wells in the Basin have nitrate levels at or above 40 mg/L (measured as nitrogen, N), which is four times the federal and state standards for drinking water (these regulatory standards are known as MCLs).

At the same time that IEUA was dealing with groundwater supply and quality issues, Orange County, the downgradient user, expressed concerns about both flow rates and high TDS loads as a result of activities within the IEUA region. In response to the need to limit the use of groundwater to the adjudicated safe-yield level and to meet downstream user needs for both quality and quantity, IEUA created, in partnership with other key Basin management players, the Groundwater Recharge Regime Program. (A description of the agreement process is provided in Section C.3.). Figure C.3 provides a graphic illustration of how the recharge regime functions. As part of the program, the recharge and desalting wells are hydrologically placed to take advantage of the groundwater gradient. The recharge of high-quality reclaimed water upgradient provides a hydrological push to help move (as well as dilute) the lower-quality groundwater in the downgradient direction. At the same time, desalter well extractions provide the pull at the low end.

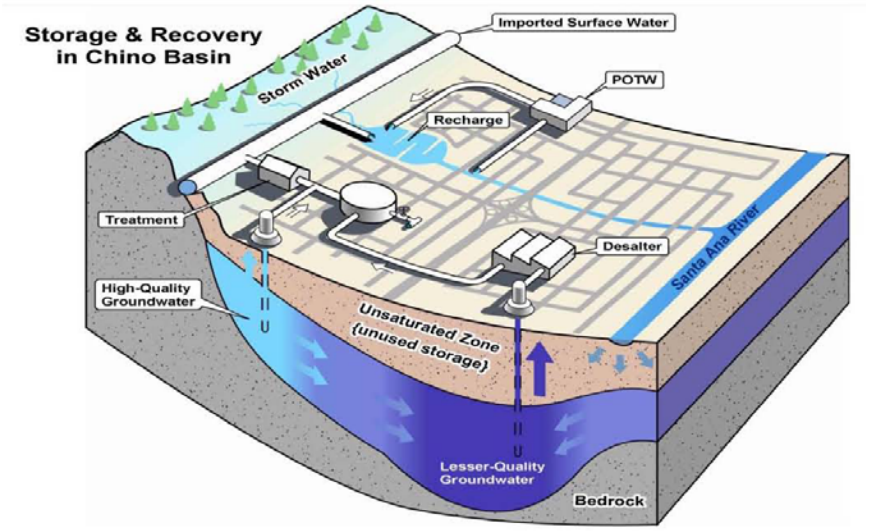

Figure C.3. Storage and recovery in the Chino Basin.

The groundwater recharge program is designed to maximize the use of all local water. High-quality stormwater and recycled water are used to recharge the Basin; desalting removes the concentrated salts downgradient, providing downstream users with a greater flow of high-quality water. In addition, the cleansing and hydrologic control of the groundwater basin achieved through the integrated deployment of recharge and desalting program elements make it possible for MWD to implement its conjunctive use and related DYY programs described in the next section.

C.2.2.2 Dry Year Yield/Conjunctive Management

The DYY program allows storage of unused imported SWP surface waters in the Chino Basin when there is extra available storage capacity. In wet years, when imported waters are relatively plentiful and relatively low in TDS, IEUA covers the costs of storing up to 100,000 AF of its excess imported supplies in the Chino Basin. In dry years, when imported supplies are limited and in high demand, the Basin's users of imported MWD waters agree to extract stored SWP imported waters from the Basin in lieu of taking their allotments from MWD.

The value of the DYY program is that it frees up scarce imported SWP waters in dry years, enabling MWD to use those limited SWP waters, waters that otherwise would be delivered to IEUA's wholesale water agencies, to satisfy the demands of its other agency customers. This increases the reliability of the imported SWP supplies for the entire MWD service area (a significant benefit for all of southern California). The DYY program also insulates the Basin's users of SWP waters from dry-year fluctuations in their imported supply (an important droughtproofing benefit within the Basin communities).

C.2.2.3 Desalters

IEUA played a key role in the development of the Chino 1 and Chino 2 desalters. Itcontinues to play a leading role today in the use of these desalters. The ability to treat groundwater with high TDS and nitrates is fundamental to the successful performance of the groundwater

recharge program. As a key member of the Chino Basin Desalter Authority (CDA), IEUA plays an integral role in the management of the Chino 1 and 2 desalters by helping to ensure proper hydraulic control of the salts within the groundwater basin and thereby enabling regulatory approval for the use of reclaimed water for Chino Basin recharge. In addition, the potable water derived from the desalters is made available to several local retail water utilities and is an important drought-resistant element of the region's water supply portfolio.

C.2.2.4 Recycled Water

Recycled water is a critical component of the Groundwater Recharge Program and of the DYY and Conjunctive Use programs described previously. Approximately 20% of recycled water is used for recharge. In 2009, approximately 21,225 AFY of recycled water was used both to recharge groundwater and for direct use.

The first pipeline for recycled water was constructed by IEUA in 1995, with deliveries to El Prado Park and golf courses in Chino and Ontario. In the late 1990s, groundwater recharge in Ely Basin also contained recycled water. With the success of these programs, IEUA developed a Recycled Water Feasibility Study in 2002. Then, in 2005, IEUA completed the Recycled Water Implementation Plan to prioritize the installation process of the regional recycled water distribution system.

The 2002 Feasibility Study and 2005 Implementation Plan included an assessment of the potential recycled water customers within the IEUA service area. Staff worked with the regional agencies to identify more than 1000 potential customers. This information was used to plan the regional and local recycled water distribution pipelines. Pipeline locations were selected to provide recycled water to the largest customers or groups of customers, resulting in a cost-effective infrastructure design.

The 2002 Recycled Water Feasibility Study recommended, and the 2005 Recycled Water Program Implementation Plan confirmed, that interconnection of all four IEUA regional treatment plants in a looped distribution system would maximize beneficial use of recycled water, increase system reliability and flexibility, and provide other operational and cost-reducing benefits. The looped system would also allow more customers to be served and provide the flexibility to release surplus recycled water to spreading basins throughout the Basin for recharge.

C.2.2.5 Stormwater Capture

Today, the Chino Basin region loses more than 40,000 AFY on the average of water that historically recharged the Chino Groundwater Basin (IEUA presentation on Water/ Energy Assets of the Chino Basin). This is primarily because of hard surfacing and flood controls that have changed the stormwater runoff pattern within the Basin. Imported water supplies have been purchased, in part, to replace stormwater. The energy value of the lost stormwater supply is 2250 kWh per AF.

The Chino Basin Watermaster identified capture of stormwater as a top priority. This high-quality source of recharge will improve groundwater quality and increase the Basin's assimilative capacity. Improvements to the flood control facilities andmodifications to the recharge basins could result in the capture of approximately 23,000 AFY (IEUA, 2010).

C.2.3 Wastewater and Discharge

As a regional wastewater service provider, IEUA uses recycled wastewater to replenish the Chino Basin, create and sell compost, and produce renewable energy. IEUA currently has five treatment plants with a total design capacity for all three of 84.4 mgd, a composting facility partially owned by the Sanitation Districts of Los Angeles County (LACSD), and several domestic and industrial trunk and interceptor lines. The current average daily flow is 58 mgd.

IEUA's regional wastewater system includes 90 miles of regional sewage interceptors. The sewage lateral pipelines are owned and maintained by the individual contracting agencies. All wastewater is treated at one of IEUA's WRPs, which provide advanced tertiary treatment that meets or exceeds all California Department of Public Health Services (Title 22 regulations) and California Regional WQCB waste discharge permit requirements.

C.2.3.1 Organics Management

To the extent economically feasible, IEUA's goals for organics management are to protect the Chino Basin from infiltration of salts and nitrogen compounds from local dairies and to treat and utilize biosolids. The Chino Basin Organics Management Business Plan has two key elements: the construction of two dairy manure digestion facilities to generate methane gas and divert salts from the groundwater, and a local organics recycling program to divert organic solids from landfill disposal. Approximately 118,000 tons of TDS (salt), 239 tons of nitrate-nitrogen, and 4,980 tons of ammonia are diverted as part of this program.

C.2.3.2 Nonreclaimable Wastewater System

IEUA owns and operates an NRW system that provides for export of high-salinity and industrial wastewater generated within the Agency's boundaries to the Pacific Ocean. The wastewater discharged to the NRW system consists mainly of industrial wastes and groundwater treatment brines (IEUA, 2007).

Use of the Santa Ana Regional Interceptor (SARI) brine line is allocated across the four SARI member agencies (IEUA and the San Bernardino Valley, Eastern, and Western municipal water districts). The line carries wastewater effluent as well as desalting concentrates. IEUA has an allocation of 7.8 mgd of SARI pipeline capacity, including discharge from its wastewater and water reuse operations, as well as brines from the CDA desalters. Brine concentrates conveyed to SARI from the Chino desalters amount to about 3.5 mgd (consisting of up to 2.0 mgd from Chino 1 and 1.7 mgd from Chino 2). This results in an export of more than 10,000 tons of salt per year from the Chino Basin. This net reduction in salts is vital to the protection of the Chino and Orange County groundwater basins.

Access to and use of the SARI brine line provides a relatively low-cost, sound environmental option for managing concentrate from the desalting operations. It enables brines, which are too concentrated to be reused in any way locally, to be blended with other treated effluent near the coast, where some areused as part of the Orange County Sanitation District (OCSD) reclaimed water program and the balance discharged at the OCSD ocean outfall. The blending of desalting brines with effluent from WWTPs may benefit the marine environment at the point of discharge by reducing the TDS differential between the freshwater effluent and the ambient salt levels in the coastal waters.

The availability of the SARI brine line is of great benefit to the Chino Basin desalting program. Absent this option, the cost (and potential environmental impact) of the inland desalting operations would probably be much greater and the regulatory feasibility much more challenging and uncertain. Where brine lines are not available, inland brine concentrate management typically is a large economic and environmental impediment to inland desalting, with a limited number of feasible options that are generally very expensive and difficult to permit.

C.2.4 Water Quality

The primary water quality challenge for IEUA relates to salt levels in Chino Basin groundwater. Elevated TDS levels, as well as elevated levels of nitrates, reflect salt issues. Some contamination by VOCs is also present. Collectively, these impair local groundwaters and make them expensive or unsuitable for supporting potable municipal and industrial (M&I) uses, as well as other uses.

The salt imbalance in the Chino Basin is a byproduct of historical agricultural use, which primarily included orange groves and vineyards along old Route 66. Starting in the 1960s, there was an influx of dairies into the lower Chino Basin region from Los Angeles County, which added to the salt buildup (in the form of nitrates). Further, some historical use of Colorado River water by local cities contributed to increased TDS levels (but not nitrates). Accordingly, Colorado River water, which has a history of elevated TDS levels, is no longer allowed to be imported for use within the Basin.

Imported SWP waters also have contributed to rising TDS levels, but primarily only during dry years. For example, in 1991, the TDS level at the SWP East Branch at Lake Silverwood was approximately 450 mg/L, but the long-term average for TDS for the past 20 years is about 320 mg/L. Background ambient groundwater is generally about 250 mg/L TDS.[10]

The rising salt levels cause several problems for water users. The water is unfit for potable uses if salt levels exceed the MCL. The water also has limited uses for other purposes, e.g., causing yield losses or other forms of damage if used for some agricultural purposes or outdoor irrigation, depending on the salt levels and the type of nonpotable use. The choice faced by impacted groundwater users is to either treat these waters (i.e., pay to desalt) or forgo use of the waters.

C.2.5 Energy

By using local supplies and implementing conservation measures, IEUA saves an equivalent of more than 50 MW of generating capacity every year. The Agency has a current energy need of 11 MW and currently self-generates about 7 MW. IEUA was recognized in July 2006 by EPA as one of the nation's top 10 local government "purchasers" of renewable energy from its own facilities. IEUA's energy portfolio includes

- A "cow power" anaerobic digester program—3 MW
- Solar power—3.5 MW

[10]. Information on TDS and nitrate levels provided by Richard Atwater (chief executive officer and general manager, IEUA), personal communication, October 2007.

- Renewable Energy Efficiency Project—minimum 65% efficiency by combining innovative processes including a Stirlingengine, an organic Rankine cycle unit, thermal energy storage, and a fuel cell
- Biogas innovation program

C.3 Background on Regulatory and Institutional Factors

To maximize the use of local waters, it was necessary for IEUA to reach out to other entities in the region and develop suitable legal and institutional relationships. This allowed IEUA and all the regional water resource users to maximize the use of all available waters. In this section, we examine the most important of these agreements.

C.3.1 The Optimum Basin Management Plan

Groundwater from the Chino Groundwater Basin is the primary source of water for IEUA and will continue to play a substantial role into the foreseeable future. However, as early as the 1930s, there was growing recognition that this local water supply was inadequate to satisfy all of the region's growing demands, which at that time reflected an economy based mostly on irrigated agriculture. The situation fluctuated over the ensuing decades, as the region went through a series of alternating multiyear wet and dry periods.

This trend was confirmed again by the end of the 1960s, when overdraft in the Chino Basin was estimated to be up to 50,000 AFY and the need for imported waters to supplement local resources was increasing. Based on experiences with other basins, by the late 1960s local water users and agencies realized that imported water would only be substituted for relatively inexpensive groundwater if pumping were limited in some way, such as through the adjudication of groundwater pumping rights (Blomquist, 1992).

By the early 1970s, adjudication looked increasingly necessary, and relevant local entities were trying to negotiate their way toward a "Watermaster" approach, with the goal of providing a high degree of self-governance to local water users. The vision was for a Watermaster to hold jurisdiction over the entire Chino Basin (as defined by hydrologic rather than political boundaries) and be endowed with policy-making powers that preserved local and flexible management programs. A key objective was to ensure the ability to define annual operating safe yields that reflected changes in Basin conditions (Blomquist, 1992).

Legal action to adjudicate the Basin's waters, initiated in 1975, resulted in a final Chino Basin Judgment in 1978. The judgment declared a safe yield of 140,000 AFY for the Basin and also empowered the newly founded Chino Basin Watermaster to set an operating safe yield each year and enabled Basin replenishment to be taken into account. It also provided for the eventual, gradual transition of safe yield from agricultural users to appropriators (i.e., local cities serving growing M&I needs) as the Basin continued to urbanize. The judgment also recognized that the vast storage capacity of the Chino Basin (with more than 5 million AF of currently unused storage) was a valuable resource and stipulated that such storage could be used by any party subject to the management of (and via signed agreements with) the Watermaster (Blomquist, 1992, pp. 277–282).

In 1988, judicial and other pressures mounted on the Chino Basin Watermaster to undertake and implement an optimum basin management program (OBMP). The OBMP is implemented by the Chino Basin Watermaster, with the objective of managing the Basin's groundwater through monitoring and recharge. Key elements of the OBMP reflect the need to

keep groundwater pumping levels up (notably in the southern, lower end of the Basin) in order to enable better and increased use of the Chino Basin's groundwater resources (and thus avoid overreliance on imported water) and preserve water quality in the Santa Ana River.

C.3.2 Santa Ana River Judgment

The groundwater recharge regime and DYY programs, briefly described in Section C.2, are a significant source of water for IEUA. Both programs are a direct result of concerns in Orange County about upstream development (the IEUA area) and the resulting degradation to both quality and quantity of Santa Ana River flows.

Litigation related to Orange County's concerns about water quality and water quantity began in the 1940s and culminated in the Santa Ana River Judgment in 1969. This judgment set both flow and water quality standards (TDS and nitrates) for the Santa Ana River at Prado Dam (the bottom end of the IEUA hydrologic area). The judgment included a provision that penalized upstream areas by requiring additional flows be provided downstream when upstream salt levels were too high (Blomquist, 1992, pp. 262–263). By instituting a regime that recognized an explicit link between water quality provided from upstream areas and the quantity of water that had to be provided to the Orange County Water District (OCWD) by upstream entities, the judgment provided incentives for upstream entities in the Chino Basin to control salt levels in the flows reaching the Santa Ana River.

C.3.3 Recharge Master Plan Implementation Memorandum

In 2002, IEUA approved the Recharge Master Plan Implementation Memorandum of Agreement with the Chino Basin Watermaster, Chino Basin Water Conservation District, San Bernardino County Flood Control District, and IEUA. These members of the Groundwater Recharge Coordinating Committee are currently working together to implement a $40 million construction project, the Chino Basin Facilities Improvement Program (CBFIP), designed to improve Basin recharge facilities.

In 2009, IEUA implemented Phase 2 of the CBFIP and added additional imported water turnout capacity, drilled monitoring wells, heightened and hardened conservation beams, and added new automated control structures to several recharge sites. Additional recharge facilities will be added in the future, and the regional implementation of stormwater best management practices in new land developments will also improve recharge. Current recharge levels by source are presented in Figure C.4.

The CBFIP helped IEUA create the flexibility necessary to reach both the OBMP goals and the water quality and quantity requirements established for OCWD through a sophisticated groundwater recharge regime.

Basin Name	Storm Water	Imported Water	Recycled Water	Total Recharge Capacity (AFY)
Pre-Existing Recharge Basins				
Ely Basin	870	1,160	870	**2,900**
Phase I Recharge Project Basins				
Banana Basin	870	1,160	870	**2,900**
Declez Basin	1,040	1,390	1,040	**3,470**
Etiwanda Ponds	0	0	0	**0**
Hickory Basin	870	1,160	870	**2,900**
Jurupa Basin	0	0	0	**0**
RP-3 Basin	1,210	1,620	1,210	**4,040**
Turner Basin	1,040	1,390	1,040	**3,470**
Subtotal Phase I:	***5,030***	***6,720***	***5,030***	***16,780***
Phase II Recharge Project Basins				
7th & 8th Street Basins	870	1,160	870	**2,900**
Etiwanda Basins	1,210	1,620	1,210	**4,040**
Lower Day Basin	1560	2,080	1,560	**5,200**
Management Zone 1:				
Brooks Street Basin	870	1,160	870	**2,900**
College Heights Basin	2600	6,070	0	**8,670**
Montclair Basins Nos. 1-4	6,940	16,190	0	**23,130**
Upland Basin	3,470	8,090	0	**11,560**
San Sevaine Nos. 1-5	8,670	11,560	8,670	**28,900**
Victoria Basin	1,040	1,390	1,040	**3,470**
Subtotal Phase II:	***27,230***	***49,320***	***14,220***	***90,770***
Total All Program Basins:	**33,130**	**57,200**	**20,120**	**110,450**

Figure C.4. Chino Basin potential water recharge capacities.

Source: IEUA, 2010.

C.3.4 Chino Basin Desalter Authority

In September 2001 the Chino Basin Desalter Authority (CDA) was established to implement the Chino Desalters Project. IEUA is responsible for managing the CDA's finances and operating the first of the two desalters, the Chino 1 desalter. Other member agencies include the Jurupa Community Services District, the Santa Ana River Water Company, and the cities of Chino, Chino Hills, Norco, and Ontario. The CDA established the percentage of ownership and the corresponding annual water delivery entitlement for each agency. To ensure the authority's financial stability, the individual entities agreed to pay for an agreed-upon amount of water regardless of the amount of water actually delivered. The CDA's goal is to produce a safe and reliable source of potable water as economically as possible for delivery to member agencies.

CDA project facilities are designed to help meet the OBMP's goal of achieving the hydraulic control needed to provide for long-term, safe, stable withdrawal from the Chino Basin and concurrently protecting the water quality of the Santa Ana River.

C.3.5 Summary of Institutional Situation

IEUA developed a system designed to maximize the use of local water through active management of the Chino Groundwater Basin. They created this flexible, high-yield, high-quality program by working together with other regional leaders. Although they face many challenges in planning for the future, they are now situated to provide a great deal of control and flexibility of their future by working with others.

C.4 Planning Challenges

The region's past as an agricultural center and its rapidly growing population and urbanization have created significant water resource management challenges for IEUA in terms of both water quality and quantity. In addition, there has been a profound change in California water supply planning in response to years of drought and recent restrictions on imported water from the Bay-Delta.

In this section, we examine these key issues facing IEUA planners, absent climate change. We also examine the important role recycled water plays in creating new supplies of water so that IEUA will continue to meet demands well into the future with local supplies.

C.4.1 Population Growth

IEUA's service area experienced one of the highest and one of the lowest growth rates within the past 10 years. In the high growth years of 2000–2007, growth rates averaged about 2.5% per year. During the period from 2008 to 2010, growth averaged about 0.5%/year (State of California, Department of Finance, E-4 Population Estimates for Cities, Counties and State, 2000–2010, with 2000 Benchmark. Sacramento, California, April 30, 2010).

The population within IEUA's service area is expected to continue growing over the next 25 years. However, the period when growth actually occurs will depend on the length of the current economic recession. The projected population for the area by 2035 is 1,181,975. This represents an increase of almost 350,000 people, with an average annual growth rate of about 1.5%.

C.4.2 Land Use

As of 2001, the total urban area within the Chino Basin had increased by 652% (from 12,300 acres to almost 80,000 acres). At the same time, the amount of agricultural land (including dairies) decreased by 51% (from 132,000 acres to 64,000 acres). Urban areas now constitute about 55% of the total land use within the Chino Basin. This trend is expected to continue, with the cities of Ontario and Chino having annexed large unincorporated areas for future use as master planned communities and commercial land (IEUA, 2010).

C.4.3 Water Demand

Overall water use has declined throughout southern California. In general, retail agencies are reporting that water demand has declined in the past few years by 10 to 20%. (*Note:*The Los Angeles Department of Water & Power (LADWP) reports that water use is the lowest in over 31 years, even though more than 1 million new residents have moved into the area.) Most water utilities attribute reduced demand to three key factors: the current economic recession, active implementation of water use efficiency programs, and the drought message being presented to the public.

In the year 2025, the population is projected to reach 1 million and water demand is projected to increase from about 244,000 AFY to approximately 340,000 AFY, an increase of about 100,000 AFY. This represents a potential 40% increase in demand with no additional improvements in use efficiency. With additional conservation, water demands are expected to increase to about 300,000 AFY (IEUA, 2005).

The service area's strong commitment to conservation and implementation of water efficiency programs as part of its regional water management strategy are expected to substantially reduce projected water demands over the next 20 years. By 2035, the region anticipates saving about 33,000 AFY, which will reduce actual water demand to approximately 300,000 AFY. The regional water use efficiency program includes full implementation of the Conservation Best Management Practices. Also, additional water use efficiency and recycled water programs and policies will ensure that all sectors maximize water use efficiency (IEUA, 2010). Figure C.5 summarizes future average water demands for IEUA's service area with and without conservation (IEUA, 2010).

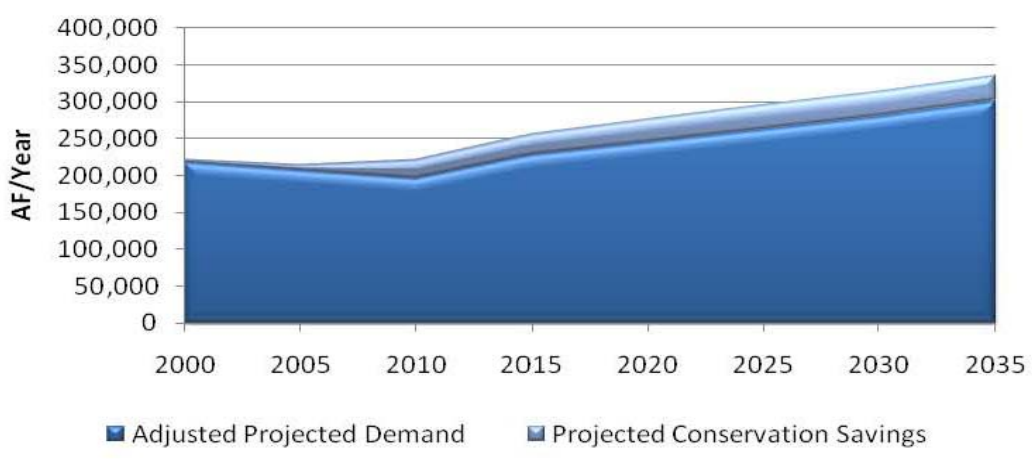

Figure C.5. Projected water demand with and without conservation.

Source: IEUA, 2010.

C.4.4 Supply Source Challenges

More than 80% of today's demand is met by maximizing the use of local water supplies, as described in Section C.2. By continuing to develop local water supplies, primarily recycled water, and implementing conservation programs, IEUA hopes to continue to meet 80% of supply needs locally throughout its 30-year planning horizon. The projected water supply mix needed to meet urban water use by source within the IEUA service area is shown in Figure C.5. The projected water use by agency is presented in Figure C.6.

Concerns about supply reliability include both issues with the San Francisco Bay-Delta and the possibility of an earthquake. Southern California's three imported water supplies (SWP, the Colorado River Aqueduct, and the Los Angeles Aqueduct) all cross the San Andreas Fault. Many other fault lines bisect major water facilities. Experts agree that it is likely that in the event of a major earthquake, one or more of these supplies will be disrupted.

IEUA plans to meet emergency demands through extraordinary conservation and groundwater pumping measures. Multiple sources of power exist throughout the region, making electrical disruptions temporary. In addition, the Chino desalters can serve as a major backup source of potable water.

C.4.5 Water Quality Issues

Groundwater quality in the Chino Basin is generally good, with better-quality groundwater found in the northern portion of the Basin where recharge occurs. Salinity (TDS) and nitrate concentrations are higher in the southern portion of the Basin. The water in about 83% of the private wells south of the 60 Freeway have nitrate concentrations greater than the MCL.

	2000	2005	2010	2015	2020	2025	2030	2035
City of Chino	15,396	15,012	15,601	16,313	18,283	20,253	22,224	22,224
City of Chino Hills	17,204	15,228	16,002	20,800	21,400	21,400	21,400	21,400
City of Ontario	42,903	42,632	33,188	44,413	49,647	54,889	60,127	70,966
City of Upland	23,038	19,847	20,841	20,330	20,330	20,330	20,330	20,330
Cucamonga Valley Water District	51,831	53,425	51,405	57,320	62,380	67,440	72,460	77,510
Fontana Water Company	44,317	41,989	44,165	43,500	46,000	48,500	49,500	50,500
Monte Vista Water District*	11,924	11,418	10,085	11,060	11,580	12,230	12,880	13,530
San Antonio Water Company	10,257	10,856	14,036	14,000	14,000	14,000	14,000	14,000
Agricultural	30,993	25,593	21,043	15,000	7,000	7,000	5,000	5,000
Potable Demand	**247,863**	**236,000**	**226,366**	**242,736**	**250,620**	**266,042**	**277,921**	**295,460**
Recycled Water	6,030	5,396	17,298	29,078	32,991	36,673	40,356	44,155
Total Demand[3]	**253,892**	**241,396**	**243,664**	**271,814**	**283,611**	**302,715**	**318,277**	**339,615**
MWD M&I Demand[4]	220,951	236,394	234,227	256,085	269,790	280,962	294,133	304,546
MWD Agricultural Demand	29,830	27,464	22,296	15,202	7,094	7,094	7,094	7,094
Total Demand	**250,781**	**263,858**	**256,523**	**271,287**	**276,884**	**288,056**	**301,227**	**311,640**

[1]Demand projections taken from local agency's UWMPs

[2]OBMP Projections – Chino Basin Watermaster assumed portion in IEUA service area

[3]Does not include conservation

[4]For comparison purposes – MWD Draft UWMP, Sept 2005, Table A.1.6

Figure C.6. Water demand projection by IEUA member agencies.

Source: IEUA, 2010.

The other constituents that have the potential to impact groundwater quality from a regulatory or Basin Plan standpoint are certain VOCs, arsenic, and perchlorate. There are also a number of point source releases of VOCs into the Chino Basin. These are in various stages of investigation or cleanup. Likewise, there are known point source releases of perchlorate (Mid-Valley Sanitary Landfill area, Stringfellow, and others) as well as what appears to be non-point-source-related perchlorate contamination from currently undetermined sources. Arsenic at levels above the water quality standard appears to be limited to the deeper aquifer zone near the city of Chino Hills (IEUA, 2010).

In addition, if the OBMP's target of pumping 40,000 AF (49.3 million m^3) of highly degraded groundwater out of the lower Chino Basin each year and treating it is to be met, an additional 12,500 AF (15.4 million m^3) will need to be pumped. This would produce approximately 11,000 AF (13.6 million m^3) of drinking water and result in the CDA's final expansion effort. The greatest challenge in completing this final expansion is the need to place the new wells in a way that will accomplish hydraulic control and capture plumes containing VOCs heading toward existing wells and proposed wells (IEUA, 2007).

C.4.6 Wastewater Issues

Throughout most of the past 10 years, IEUA has been in a phase of rapid construction and expansion, including two major wastewater facility expansion projects that provided a net treatment capacity increase of 17 mgd. The flow forecast for the next 10 years indicates much slower growth. As a result, the 2010/2011 Ten Year Capital Improvement Plan (TYCIP) includes no budget for WWTP expansions.

Since the current drought started in FY 2006/2007, both water consumption and wastewater generation in IEUA's service area have been trending downward.In FY 2008/2009, with the recorded increase of 1314 equivalent dwelling units (EDUs) in the service area, IEUA would have expected to see an increase of up to 360,000 gpd in total raw sewage influent into the regional sewerage system (estimated using a wastewater generation factor of 270 gpd/EDU). Instead, the average daily flow rates of raw sewage into the regional WRPs have decreased by approximately 1 mgd. Los Angeles County and Orange County sanitation agencies have also experienced a leveling off or decline in wastewater flows over the past few years. This trend, to some extent, may reflect the decrease in economic growth and the increase in area foreclosures. However, the decline is expected to continue for the next few years, even after the economy rebounds, as conservation continues (IEUA, 2010).

C.4.6.1 Organics Management

It is important to note that even though wastewater flows are decreasing, the concentrations of organic matter and suspended solids in the wastewater are increasing roughly proportionately. More solids are removed from the wastewater during treatment, requiring more solids-handling capacity.

In FY 2008/2009, with the recorded increase of 1314 EDUs in the IEUA service area, IEUA would have expected to see an increase of about 360,000 gpd in total raw sewage influent into the regional sewerage system. Instead, the average daily flow rates of raw sewage into the regional WRPs showed no measurable increase. IEUA expects this trend of static or declining wastewater generation rates to continue over the next few years (IEUA, 2010).

C.4.6.2 Brine Management

Even though the SARI brine line facilitates the cost-effective and sound management of concentrates from the Chino desalters today, future growth will increase challenges related to the finite capacity of the line. Not only is expanded desalting activity anticipated for CDA and other entities in the Santa Ana River watershed, butalso growth is anticipated of other activities that will compete for brine line capacity, including higher volumes of wastewater, as well as effluent from perchlorate removal efforts.

C.4.6.3 Other

In 2000, Parsons Engineering Science evaluated future funding needs and long-term issues to maximize wastewater treatment cost effectiveness for IEUA. The Parsons study suggested (1) diverting more high-salinity wastewater flow from the Regional System to the NRW system, thereby reducing the need for expansion of the Regional System; and (2) melding the NRW user rates and charges with the Regional system (IEUA, 2007).

C.4.6.4 Infrastructure Needs

Under the OBMP, more than $350 million was invested in capital improvement projects from 2000 to 2007, including desalters, recharge improvements, new wells and on-site well head treatment, recycled water distribution systems, and the 100,000-AF conjunctive use storage agreement with MWD (IEUA, 2005). In 2007 IEUA, the Watermaster, and CDA invested an additional $250 million to expand desalters, continue recycled water development, implement new recharge improvements, and expand the MWD conjunctive use storage agreement (IEUA, 2008).

C.4.6.5 Financial Issues

Over the last three fiscal years, IEUA significantly decreased both its capital and operations and maintenance (O&M) costs in response to the economic recession and the drastic slowdown in development in its service area. To date, nearly $200 million of nonessential capital projects have been deferred, most of which were originally included in the FY 2008–2017 TYCIP adopted in June 2008. Implementation of the Cost Containment Plan in FY 2008/2009 resulted in reductions of nearly $7 million in operational costs. At the same time, they expedited O&M of the recycle water plan to take advantage of low construction costs and funding opportunities provided by Proposition 50.

According to California economist Dr. John Husing of Economics & Politics, Inc., an economic recovery is not expected until 2012 or 2013 on a national level, and even later for California, particularly southern California. In light of the bleak economic conditions, IEUA shifted the focus of its capital program from expansion to repair and replacement of existing facilities. Beginning in FY 2007/2008 and continuing through FY 2008/2009, the Agency and the Board deferred more than $200 million of noncritical capital projects originally included in the FY 2007/2008—FY 2016/2017 TYCIP. Most of these projects were slated to begin in FY 2007 through FY 2010. The deferred capital projects were primarily expansion and improvement projects for the wastewater system that were based on the assumption that the area's population would continue to grow through 2025. One exception is the Recycled Water Business Plan, which was adopted by the Board in December 2007 for expansion of IEUA's recycled water distribution system. The Recycled Water Business Plan, driven by a reduction in the available potable water supply, contained an aggressive program to increase

the use of recycled water within the Agency's service area to meetgrowing demands (IEUA, 2010).

C.4.7 Uncertainties

As IEUA faces the challenges of planning for the future, itmust address the following uncertainties: population growth and changes in water usage, the reliability of both local and imported water supplies, the ability to raise funds given the current and projected economic challenges, the ability to bring together innumerableparticipants, and the public's perception of needs (IEUA, 2005).

C.5 IEUA Short- and Long-Term Planning

IEUA designed a great deal of flexibility into its water management system. In this section, we examine IEUA's approach to planning and how the development of an extensive reuse program is key to their ability to increase supply without increasing the purchase of expensive imported waters.

C.5.1 Key Utility Objectives

In their 2009 annual report, IEUA placed sustainability as its top priority. To achieve this goal, itplans to recharge the Chino Basin. More than 10,000 AF of new water was recharged in 2009. Specifically, IEUA addressed the need for an increase in supply through an expansion of the groundwater management program described in Section C.2. The plan calls for an increase in the use of the Chino Basin by about 75% to about 165,000 AF and an increase in recycled water supply for direct use to about 69,000 AF.

Additional priorities identified during the 2005 planning process were renewable energy generation, organics management, and phased treatment plant expansion. Planning for water shortages and catastrophic interruptions was also identified as a planning priority.

C.5.2 The Regional Water Management Plan

The California Urban Water Management Act requires utilities to update their UWMPs every five years. In February 2011, a draft of the 2010 UWMP was released for review. This draft report provides a review of the implementation of the 2005 UWMP including the Water Use Efficiency Plan and the Water Recycling Plan.

Over the last five years, IEUA and the regional retail water agencies developed a strong partnership and a coordinated approach to conservation management measures that reduce water use.Figure C.7 shows the amount of "new" water conserved over the past five years (not including water saved prior to 2005) and how that affects the retail agencies financially. The avoided imported water purchases, at the Tier II rate, are approximately 7600 AF, which is equivalent to about $3.8 million.

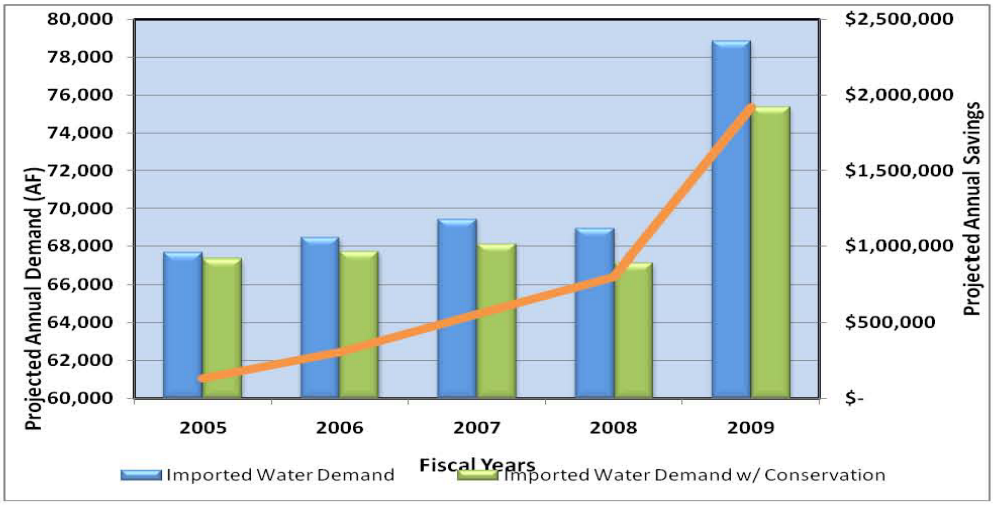

Figure C.7. IEUA's Tier II costs avoidedthrough conservation over past years.

Source: IEUA, 2010.

C.5.3 The Water Recycling Plan

The 2010 IEUA Statement of Reuse is as follows:

Recycled water can be used for a number of applications including Irrigation, Industrial Processes, Groundwater Recharge, and Environmental Enhancement. The goal of the IEUA is to achieve maximum reuse of all available recycled water.

In 2007 IEUA adopted an aggressive three-year business plan designed to increase use of recycled water. The goals of the plan are to provide 50,000 AFY to meet anticipated demand by June 2012; provide 100,000 AFY of recycled water in the future; make the recycled water program self-funding through sales and MWD rebates; and keep construction costs below $250 million. Figure C.8 provides a graphic illustration of current and short-term projected recycled water demand. Figure C.8 shows, by year, the increase in projected demand and the associated increase in sales.

IEUA's adopted Recycled Water Feasibility Study (August 2002) indicated that by the year 2020 the projected use of recycled water would exceed 70,000 AFY, with more than 1700 customers projected to be connected to the regional recycled water distribution system. Subsequent implementation of the 2005 Recycled Water Program Implementation Plan and the 2005 IEUA UWMP showed that more than 93,000 AFY of recycled water could be delivered to more than 1900 potential customers. IEUA will recharge up to 33,000 AFY of this recycled water (blended with stormwater and imported water to meet the overproduction replenishment needs) into the Chino Basin and facilitate direct delivery of more than 60,000 AFY of recycled water to local customers.

Year		Connected Demand	Increase		Estimated Sales*
		AFY	AFY	%	AFY
Base Year	2006/07	13,000		---	---
1	2007/08	17,600	4,600	135%	13,500
2	2008/09	27,034	14,034	208%	16,000
3	2009/10	36,000	13,000	277%	32,000*
4	2010/11	45,000	32,000	346%	40,000*
5	2011/12	50,000	37,000	385%	45,000*

*Estimated sales lag connections.

Figure C.8. Recycled water three-year business plan annual goals for connected demand and sales.

Source: IEUA, 2010.

IEUA's goal is to use as much recycled water for local beneficial uses as is economically practical, as well as to replenish the Chino Basin. In June 2007, IEUA received a new permit for recycled water recharge, adding several more basins that can be utilized for recharge with recycled water. These added basins will increase both the volume and distribution of recycled water in the Chino Basin.

In 2009 recycled water use totaled about 32,362 AF; 12,970 AFY was used for outdoor irrigation, 2,106 AF was used for industrial processes, 10,993 AF was used for agriculture, and 6294 AF was used for groundwater recharge. As a result of a revised regionwide permit, recharge will increase rapidly over the next few years. The remaining supply of recycled water, about 32,638 AF, was discharged to the Santa Ana River for reuse in Orange County.

Available recycled water supplies are projected to reach 107,400 AFY in 2020. In conformance with the 1969 Santa Ana River Judgment, a minimum of 17,000 AFY of water will be discharged to the Santa Ana River. This leaves more than 86,000 AFY of recycled water available for beneficial reuse within the IEUA service area by 2020.

IEUA's overall goal is to achieve maximum reuse of all available recycled water. In the short term, the primary focus of IEUA's recycled water program will be the connection of industrial and landscape customers and development of facilities to ensure cost-effective delivery of recycled water to groundwater recharge spreading sites. In the long term, IEUA seeks to construct a looped distribution system that will interconnect IEUA water reclamation plants, ensure reliability of direct supply to customers, and maximize the flexibility to recharge all surplus recycled water in flood-control spreading grounds.

IEUA believes that development of local recycled water facilities will be the key to expanding the direct use of recycled water. Direct uses include irrigation for landscaping, industrial process and cooling, and recreational uses such as decorative fountains. As the recycled water facilities expand for the first time into cities such as Fontana and Upland, IEUA will be looking to the local water providers to construct sufficient recycled water facilities that will reduce their dependence on imported water from MWD's Rialto Feeder.

All future direct use (landscape and industrial customers) of recycled water will be given priority service over recharge deliveries. Recharge will be credited based upon the annual flow contributions for all contracting agencies on a prorata basis.

Figure C.9 provides projections for total regional recycled water usage between 2010 and 2035.

To deliver the ultimate demand for recycled water additional regional pipelines, reservoirs, booster stations, and land parcels will be required. As outlined in Figure C.10, approximately $101.5M in capital improvements will be required.

C.5.4 The Drought Management Plan

Since calendar year 2007, critically dry conditions have affected all of MWD's main supply sources. In addition, a ruling in a federal court in August 2007 provided protective measures for the Delta smelt in the Sacramento-San Joaquin River Delta that createduncertainty about future pumping operations from the SWP. This uncertainty, along with the impacts of dry conditions, raised the possibility that MWD would not have access to the supplies necessary to meet total firm demands and would have to allocate shortages in supplies to its member agencies. In 2009, IEUA worked with member agencies to develop a water supply allocation plan (WASP) to address these issues.

As a part of its WASP, IEUA developed a drought management plan. The purpose of that plan is to implement the MWD WASP in a manner that ensures equity and fairness, avoids DYY penalties, and recognizes IEUA/MWD investments in local efforts to droughtproof the IEUA region. The drought management plan is also designed to encourage additional local investments to further droughtproof the economy; enhance conservation; increase utilization of recycled water by connecting parks, schools, and other landscapes; promote flexibility through the Azusa pipeline; increase Chino desalter deliveries to the maximum; increase groundwater recharge; and coordinate the IEUA service area communication strategy.

Category	2010	2015	2020	2025	2030	2035
Recharge	6,294	25,000	28,000	35,000	35,000	35,000
Industrial	2,106	6,000	10,000	17,000	17,000	17,000
Irrigation	12,970	40,000	45,000	49,000	49,000	49,000
Agricultural	10,993	3,000	3,000	3,000	3,000	3,000
Total	**32,362**	**74,000**	**86,000**	**104,000**	**104,000**	**104,000**

Figure C.9. Projected recycled water usage (AF).

Source: IEUA, 2010.

Projects	Metric	Demand (acre-ft/yr)	Cumulative Demand (acre-ft/yr)	Construction Cost ($ Million)	Capital Cost ($ Million)	Priority
PRV Station	**Capacity (gpm)**					
Station from 1158 to 1050 (16" valve)	7,000			$0.16	$0.2	A
Prado Lake Discharge Control Valve	2,000			$0.3	$0.38	A
Total Priority A Projects		**0**	**36,362**	**$0.4**	**$0.5**	**A**
Pipeline Projects	**Length (ft)**					
1299 E Pipeline	12,700	1,500		$3.6	$6.8	B
Church Street Lateral	4,200	200		$1.9	$2.5	B
1630 E Pipeline,	12,700	8,500		$5.2	$10.5	B
Reservoir Projects	**Size per Tank (MG)**					
1299 East Reservoir Conversion	3.5			$3.4*	$10.9*	B
Booster Station Projects	**Size (HP)**					
1630 East Booster Station	1,200			$3.4*	$10.9*	B
Monitoring Wells and Lysimeters	**Wells / Lysimeters**					
Victoria and San Sevaine Basin	3 / 2			$0.8	$1.5	B
Total Priority B Project		**10,200**	**42,562**	**$14.9**	**$32.2**	**B**
Pipeline Projects	**Length (ft)**					
930 Zone Pipeline	1,250	5,000		$8.5	$11.7	C
Northwest Recycled Water Pipeline	30,000	1,300		$19.3	$24.1	C
Northwest Recycled Water Laterals	12,330			$3.0	$3.8	C
Reservoir Projects	**Size per Tank (MG)**					
930 Reservoir	5			$7.8	$11	C
1630 W Reservoir	3			$5.3	$6.6	C
Booster Station Projects	**Size (HP)**					
RP-5 Zone Booster Station Expansion	750			$3.0	$3.6	C
1630 W Pump Station	450			$3.3	$4.0	C
CCWRF R.W. P.S Expansion	1,250			$0.54	$1.0	C
RP-1 South Zone R.W. P.S. Expansion	500			$0.44	$1.0	C
Total Priority C Projects		**6,300**	**48,862**	**$51.2**	**$66.8**	**C**
Pipeline Projects	**Length (ft)**					
Wineville Extension	5,300	419		$1.3	$2.0	D
Total Priority D Projects		**419**	**49,281**	**$1.3**	**$2.0**	**D**
All Projects – Priority A through D		**16,919**	**49,281**	**$67.8**	**$101.5**	

* costs are the same for 1630E. Recycled Water Pump Station and 1299 E. Recycled water Reservoir Conversion

Figure C.10. CIP for recycled water.

Source: IEUA, 2010.

C.5.5 Planning for Reductions in Energy Costs

IEUA's strategies to further reduce energy costs include

- Maximizing local water supplies to increase locally controlled droughtproof supplies and reduce more costly imported supplies
- Implementing green development standards for new housing in the most rapidly growing region in California
- Increasing on-site energy production, including biogas, solar, wind, hydro recovery, and combined heat and power systems
- Reducing water-related energy end use by partnering with electric and gas utilities to increase efficiency of operations

C.6 IEUA and Climate Change

IEUA is lucky to have a wide selection of climate change documents, studies, and other information sources to use in planning for climate change. The most important of these include the California Climate Change Center; the PPIC report, *Climate Warming & California's Water Future;* and the RAND Institute report, *Preparing for an Uncertain Future Climate in the Inland Empire*.

In this section, we examine the sources of climate change information available to IEUA, review the inputs and outputs of the models, and examine the uncertainties associated with the findings. We also look at IEUA's current response to projected climate changes.

C.6.1 California Climate Change Center

In 2006 the California Climate Change Center and California Energy Commission stated that for the IEUA region, temperatures are very likely to increase and average annual precipitation may either increase or decrease. These trends are expected to have significant impacts by increasing demand for irrigation; generating more intense and possibly less frequent storms; diminishing the Sierra snowpack, which provides imported water supplies; and decreasing local groundwater recharge.

These projections are based on GCMs, with all the inherent uncertainties associated with modeling at this level. This level of uncertainty is a fairly standard result because GCMs provide a wide range of potential climate changes. Note that precipitation may either increase or decrease, making it a difficult projection for planners.

C.6.2 CALVIN Model

The University of California-Davis's Center for Environmental and Water Resource Engineering developed an economic–engineering optimization model, CALVIN, to look at a wide range of water management options for the State of California. The CALVIN model was run explicitly for IEUA with applicable inputs. The CALVIN model is designed to illustrate the likely effects of a range of climate-warming estimates on the long-term performance and management of California's water system, including groundwater and surface water, agricultural and urban water demands, environmental flows, hydropower, and potential for managing water supply infrastructure in order to adapt to changes in hydrology caused by climate warming (Draper et al., 2003).

The CALVIN model was run for IEUA with a range of likely potential climate impacts derived from GCMs. CALVIN modelers selected the GFDL CM2.1 model (NOAA Geophysical Dynamics Laboratory, Princeton, NJ) with the A2 (relatively high emissions) scenario for this study. Climate-altered hydrologic inflows and reservoir evaporation for more than 150 locations in California's water supply system were then estimated by changing the order of the 72-year monthly unimpaired historically based flow record following the method presented by Zhu et al. (2005). This approach preserves the interannual variability of the hydrologic system and incorporates changes in seasonal patterns and volumetric totals. Climate change ratios for monthly stream flows were obtained by comparing GCM downscaled monthly averages (Maurer et al., 2007) for the 30-year time periods of 1965–1994 and 2070–2099.

Ratios indicate an earlier snowmelt, with stream flows increasing slightly in January and February but decreasing in all other months. These ratios were applied to historical surface water flows to produce the new climate change time series.

The downscaled effects of this scenario were used to estimate meteorological conditions for a 30-year period centered on 2085. Results indicate a 2 °C average increase in temperature and a 3.5% decrease in precipitation in California's Central Valley. The study solely addressed climate warming and did not look at climate variability or SLR that is due to human-induced changes in climate.

Based on this, the modelers chose to look at two alternative potential climate conditions:

- A dry warming scenario identified from Parallel Climate Model 2 (PCM-2)
- A wet warming scenario identified in the hybrid climate model (HCM)

The CALVIN hydrological model looks at the entire interconnected California water system, including surface water and groundwater, with more than 1200 spatial elements, 51 surface reservoirs, 28 groundwater links, 600 + conveyance links, 88% of irrigated acreage, and 92% of the population. By inputting the potential climate-warming scenarios into the HEC-PRM with a network flow optimization solver developed by the USACOE (Draper et al., 2003), the CALVIN modelers could now prescribe how the California water system operation would function over a 72-year monthly time series of hydrology.

The model design allows users to look at how California water infrastructure could adapt and respond to changes in climate, in the context of higher future populations, changes in land use, and changes in agricultural technology. Unlike traditional simulation modeling approaches, this economically optimized re-operation of the system to adapt to climate and other changes is not limited by present-day water system operating rules and water allocation policies, which by 2100 are likely to be seen as archaic (Draper et al., 2003).

The model's authors identify the key weaknesses of the model as the need for improvements in deep percolation and reservoir evaporation representations and consideration ofaltering flows by yeartypes, rather than having all years altered by the same monthly factors.

The study concludes that the most limiting type of facility for the year 2100 is conveyance capacity. This is especially true for southern California, where present Colorado River Aqueduct and California Aqueduct capacities to deliver water to Los Angeles, San Diego, and other parts of metropolitan southern California are used to their limits in all 2100 scenarios. This implies that urban users in these regions must be creative about new water

supply technologies and the employment of water conservation and water use efficiency. For 2100, Southern California employs considerable quantities of new water supply technology, averaging 1.4 million AFY of additional wastewater recycling and 0.2 million AFY of sea water desalination. Although these are large contributions by present-day standards, they represent only a modest proportion of Southern California's 2100 urban water demands (CALVIN).

C.6.3 RAND Study

In the RAND study, "Preparing for an Uncertain Future Climate in the Inland Empire," researchers worked with IEUA to identify vulnerabilities related to climate change in its long-term water plans and to evaluate its most effective options for managing those risks.

In the first modeling step, future climate scenarios were generated using two approaches: extrapolations of past conditions in the IEUA area and statistically generated temperature and precipitation time series using results derived from a number of global-scale models that capture GHG-driven climate change.

RAND found that by assuming that the GCMs are valid representations of future climate dynamics, one can look at the range of predicted temperature and precipitation changes throughout southern California. According to 21 GCMs, the likely range (±1 standard deviation of the mean projected increase) of average summertime temperature increase is projected to be between 0.1 and 2.1 °C. The likely range of average wintertime precipitation trends is projected to be a decrease of between 19% and 8% (Tebaldi et al., 2006).

Because the scale of estimates from the GCMs wastoo coarse to be useful in modeling IEUA's hydrology, David Yates of NCAR applied a regional downscaling procedure called K-nn (Yates et al., 2003) to project regional-scale climate changes in temperature. It was still necessary to draw a correlation between the changes in temperature and any resulting changes in precipitation. Most climate models suggest that strong warming will deepen persistent drought in the subtropical region; IEUA is at the northern edge of this boundary. This effect suggests a strong negative relationship between temperature and precipitation. However, if El Niño conditions are disproportionately strengthened as warming trends continue (which has a high probability),the region could then experience warmer temperatures and more tropical storms, which would be consistent with a positive relationship. RAND assumed that the driest (wettest) precipitation decile corresponds to the warmest (coolest) temperature decile.

RAND placed the climate scenarios generated by the GCMs and downscaling into WEAP, which was developed by the Stockholm Environment Institute. WEAP is based on a set of supply-and-demand relationships represented by nodes. The nodes represent IEUA catchments, indoor-demand sectors, surface supplies, and groundwater basins. Rivers, conveyance facilities, and other flows link the nodes.

In the next step, RAND looked at how effective IEUA's planning scenarios, as described in their 2005 IEUA Regional Urban Water Plan (IEUA, 2005), are at keeping the need for both increasing purchases of imported waters and surplus supplies of water minimal. RAND used itsmodeling expertise to evaluate effectiveness in three ways: a traditional scenario analysis, a probabilistic analysis, and a RDM analysis. The models identified changes in demand, available supply, annual shortages, financial effects of shortages, and cost of provisioning supply. These outcomes were then summarized as the present value of costs and financial

effects of shortages. RAND also looked at the effectiveness of the RUWMP if either the recycled water program or groundwater-replenishment program (both programs contribute significant future water supplies) were not fully implemented.

In the first analysis, the traditional scenario, two important uncertainties were chosen to vary: (1) the strength of the climate change signal embedded in the monthly weather sequences and (2) IEUA's ability to meet its recycling and replenishment goals. For the first variable, RAND selected two climate change ranges: (1) slightly warmer and (2) hotter and drier. For the second variable, RAND chose to model two levels of the IEUA's ability to meet their planning goals for recycling and replenishment. By combining the two variables, four scenarios were developed.

Under the slightly warmer scenarios, there were no projected shortages regardless of IEUA's ability to meet recycling or replenishment goals. Under the hotter and drier scenarios, shortages were projected, particularly when the recycling and replenishment goals were not meet. Figure C.11 shows the performance of the four modeled standard scenarios. Assuming large surpluses are not cost-effective, it is less desirable for IEUA to have surplus water supply (even if it means declining purchases of high-priced imports, selling it to others, or devoting more to environmental purposes) than to forgo the costs of developing or securing the local resources that lead to overabundance in supply.

As a statistical-discovery analysis, this traditional decision analysis identified three conditions that need to exist simultaneously for IEUA's plan to lead to large future costs: (1) large declines in precipitation, (2) large changes in import availability and cost, and (3) small or large reductions in natural percolation in the Chino Basin.

The traditional scenario analysis provided a simple description of a range of future conditions relevant to IEUA. It is, however, limited because the choice of scenarios can appear arbitrary and the approach provides no systematic means to compare alternative policy choices.

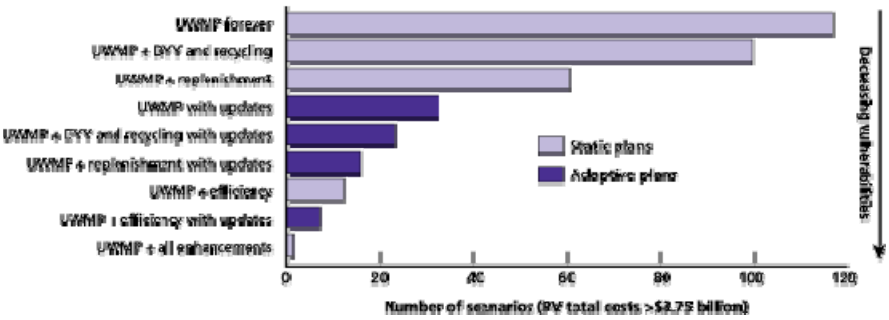

Figure C.11. IEUA planning scenarios.

Source: IEUA, 2010.

In the probabilistic scenario, a large ensemble of plausible scenarios, based on the same variables as in the standard scenario, climate change, and IEUA's plans, were weighted by bestavailable probabilities. Ninety weather sequences were modeled nine times—one for each

possible combination of missing, meeting, and achieving recycling and replenishment goals. The ability to model a large number of scenarios allowed for the climate sequences to be taken from the entire range of modeled climate change possibilities—not just the tails, as seen in the standard scenario. These 810 simulation results were then weighted according to their joint probability of occurring. Then each of the four water management plans was evaluated against the 810 probability-weighted scenarios.

The probability-weighted scenarios suggest that if one believes the bestavailable probabilistic information about both future climate and IEUA's ability to meet their recycling and replenishment goals, the IEUA RUWMP can ensure that the chance of a shortage over the next 25 years will not exceed 7%. All four plans performed well. They all had low probabilities of shortage and led to probability-weighted surpluses of between 20 and 40 trillion AF (considered good).

Probabilistic scenarios can provide a concise ranking of the desirability of alternative IEUA plans but can lead to errors of omission in planning by downplaying the potential importance of possible future scenarios that deviate from likeliest conditions. Further, effective use of probabilistic scenarios may require a wide range of stakeholders to agree on the validity of the distributions used in the analysis.

One caveat of the probabilistic approach is that performance is considered for each year independently of any other. In all likelihood, drought years may come back to back and therefore result in larger shortages.

A key objective of the RDM analysis is to evaluate a broad range of possible outcomes and improve our understanding of the conditions that lead to unfavorable outcomes. The RDM analysis did not require a detailed assessment of probabilities and allowed for a large ensemble of many runs of the simulation model that considered a broader set of factors that are considered uncertain, including hydrologic time series, urban water demand, supply reliability, and effectiveness of management strategies.

Similarly to the probabilistic assessment for the RDM analysis, RAND evaluated 90 weather sequences reflecting the NCAR-estimated climate trends over the IEUA region and the 9 combinations of achievement levels of recycling and replenishment goals used for the probabilistic assessment. Three important concerns that IEUA had about future management conditions were also modeled: (1) level of natural improvement in household water-use efficiency because of new, more water-efficient development; (2) reduction in the permeability of the Chino Basin that is due to continued urbanization and increases in the intensity of precipitation events; and (3) the effect that climate change would have on imports from the SWP (Chino Basin Watermaster, 2007).

The simulation, using a cluster-finding algorithm called the patient rule induction method (PRIM), was used to find and characterize clusters in the database of simulations that represent management conditions underwhich the 2005 UWMP performs poorly. The results suggest two clusters of simulations that have low performance. The first, the dry, flashy, low-recycling scenario, reflects conditions in which climate change reduces annual precipitation in the region significantly, has low infiltration to the Chino Basin (due in part to more flashy storms), and has recycling levels lower than anticipated. The second cluster, the wet effective-recycling scenario, is defined as cases in which the recycling goals are exceeded and weather sequences are wetter.

RDM results suggest that no single plan evaluated is robust, that is, no single plan performed adequately well across all three scenarios. This result is similar to the results from the traditional scenarios, but with two important differences. First, RDM results indicate that the two scenarios account for 334 of the 532 poor outcomes. Traditional scenario analysis provided no such information about the quality of the scenarios generated. The higher the proportion of bad cases covered by the scenarios, the more confident one can be that the critical risks to the management plans are characterized. Second, results from the standard scenarios do not differentiate between the importance of the recycling and replenishment goals—the RDM results suggest that the former are more critical to the success of the plan.

Based on this modeling exercise, IEUA could now consider more carefully how likely it thinks the scenarios are. For example, it could accept the probabilistic climate change information provided by NCAR, use the subjective assessments of the achievement levels for recycling and replenishment, and seek additional information to calculate what the probability is of the dry, flashy, low-recycling scenario. As an example of this, RAND used the NCAR information, the subjective assessments of recycling and replenishment, and assumed uniform distributions for percolation decrease parameter to estimate the probability of the dry, flashy, low-recycling scenario. A rough estimate suggests that it is 30% likely, which creates a tipping point for IEUA.

The RAND model also found that when the UWMP is allowed updates and enhancements as illustrated in Figure C.11, IEUA, although still vulnerable to large declines in precipitation, is actually more vulnerable to future high demands. When DYY and recycling are used as enhancements, IEUA is still vulnerable. However, rather than being vulnerable to high demand, IEUA is more vulnerable to the high cost of imports. In sum, the study found that water shortages are not a key issue for IEUA and that all enhancements pay off, as they allow the region to reduce expensive imports. RAND summarized their findings by suggesting that IEUA can "reduce exposure to adverse climate-change effects by taking advantage of the favorable economics of local resources development, as long as these activities are less costly than imports and precipitation trends under climate change are flat to strongly decreasing" (RAND, 2008).

C.6.4 IEUA Current Climate Change Strategy

In the 2011 Draft RUWMP update, IEUA states that its current approach to climate changes includes

- Proactively working with state policymakers and legislators to target incentives in support of our energy-saving and water-saving projects
- Working with ACWA to encourage federal and state policy to incentivize and provide financial assistance for local resource investment in conservation and water use efficiency, recycling, and renewable energy
- Working with SAWPA to develop integrated, regionally coordinated water resource plans and projects that can be implemented on a watershed basis and that are eligible for Department of Water Resources
- Using the "First Thursday" Prado Basin Planning Process to work with local stakeholders, such as regulators, communities, developers, recreation interests, and environmental interests, to implement new stormwater programs in a cost-effective way that reduces runoff from hard surfaces and promotes groundwater infiltration and water quality improvement

- Working with the Southern California Alliance of Pots (SCAP), CASA, and the CWCCG to maintain active and consistent involvement with the state's Air Resources Board, as they develop and implement the AB 32 Scoping Plan and regulations
- Promoting AB 32 implementation measures that ensure wastewater agencies receive credit for early, voluntary reductions in GHG emissions; are able to participate in the production and exchange of renewable energy credits under a proposed cap-and-trade system; and are treated fairly under proposed mandatory GHG reporting regulations and fee systems
- Working with the MWD on planning efforts such as the integrated regional planning process and preparing technical tools and decision-support models for incorporating climate change uncertainties into the water planning process

C.6.5 Summary of IEUA's Approach to Climate Change

The California Climate Change Center projects that temperatures will increase and precipitation is likely to either increase or decrease, with diminishing snowpacks. The CALVIN modeling study concludes that southern California needs to find itsown water sources for future increases in demand, because the state conveyance system will prevent any increases in supply given potential climate changes. The RAND study concludes that as long as IEUA allows itsplans to be modified and adjusted as needed, they are efficient and effective as designed.

The IEUA's short- and long-term plans have built-in flexibility because ofits basic principle of maximizing every drop of water within itscontrol, including recycled water. It is able to effectively manage itswater sources by building relationships with other users.

Evaluating Long- and Short-Term Planning Under Climate Change Scenarios to Better Assess the Role of Water Reuse

About the WateReuse Research Foundation

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

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

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Acronyms and Abbreviations

ACWA	Association of California Water Agencies
ADEQ	Arizona Department of Environmental Quality
ADWR	Arizona Department of Water Resources
AOGCM	atmosphere–ocean general circulation model
ASLD	Arizona State Land Department
ASR	aquifer storage and retrieval
AWWA	American Water Works Association
BCE	business case evaluation
BCSD	bias-corrected statistical downscaled
BIC	Buckeye Irrigation Company
CALVIN	California Value Integrated Network
CAP	Central Arizona Project
CASA	California Association of Sanitation Agencies
CBFIP	Chino Basin Facilities Improvement Program
CCWRP	Cave Creek Water Reclamation Plant
CDA	Chino Basin Desalter Authority
CERP	Comprehensive Everglades Restoration Plan
CIP	capital improvement program
CLIMAS	Climate Assessment for the Southwest
CMIP3	Coupled Model Intercomparison Project 3
CO_2e	carbon dioxide equivalents
CWCCG	California Wastewater Climate Change Group
DBP	disinfection byproducts
DSPM	decision support planning model
DST	decision support tool
DYY	dry-year yield
EDU	equivalent dwelling unit
ENSO	El Niño/Southern Oscillation
EPA	U.S. Environmental Protection Agency
F.A.C.	Florida Administrative Code
FDEP	Florida Department of Environmental Protection
FPL	Florida Power and Light Company
F.S.	Florida Statutes
GCM	global climate model (as well as general circulation model)
GFDL	Geophysical Fluid Dynamics Laboratory

GHG	greenhouse gas
GIS	geographic information system
HCM	hybrid climate model
HEC-PRM	Hydrologic Engineering Center's Prescriptive Reservoir Model
IEUA	Inland Empire Utilities Agency
I&I	infiltration and inflow
IPCC	Intergovernmental Panel on Climate Change
IWA	International Water Association
LACSD	Sanitation Districts of Los Angeles County
LADWP	Los Angeles Department of Water & Power
MAGICC	Model for the Assessment of Greenhouse-Gas Induced Climate Change
MCL	maximum contaminant level
MDWASD	Miami–Dade Water and Sewer Department
M&I	municipal and industrial
MWD	Metropolitan Water District of Southern California
NARCCAP	North American Regional Climate Change Assessment Program
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NWR	nonreclaimable wastewater
OBMP	Optimum Basin Management Program
OCSD	Orange County Sanitation District
OCWD	Orange County Water District
O&M	operations and maintenance
PAS	pharmaceutically active substances
PCM-2	Parallel Climate Model 2
PPIC	Public Policy Institute of California
PRIM	patient rule induction method
PWSD	City of Phoenix Water Services Department
RCM	regional climate model
RDM	robust decision making
RID	Roosevelt Irrigation District
RIT	rapid infiltration trench
RUWMP	Regional Urban Water Management Plan
RWA	Regional Water Availability

SARI	Santa Ana Regional Interceptor
SAWPA	Santa Ana Watershed Project Authority
SCAP	Southern California Alliance of Pots
SDWA	Safe Drinking Water Act
SFWMD	South Florida Water Management District
SLR	sea level rise
SRES	Special Report on Emissions Scenarios
SROG	Sub-regional Operating Group
SRP	Salt River Project
SRPMIC	Salt River Pima-Maricopa Indian Community
SSO	sanitary sewer overflow
SWP	State Water Project
SWTR	Surface Water Treatment Rule
TBL	triple bottom line
TDS	total dissolved solids
TOC	total organic carbon
TYCIP	Ten-Year Capital Improvement Plan
UNEP	United Nations Environment Programme
USACOE	U.S. Army Corps of Engineers
USBR	Bureau of Reclamation
USGCRG	U.S. Global Change Research Group
USGCRP	U.S. Global Change Research Program
UWMP	Urban Water Management Plan
VOC	volatile organic compound
WASP	Water Supply Allocation Plan
WCA	Water Conservation Area
WCRP	World Climate Research Programme
WEAP	Water Evaluation and Planning Model
WEF	Water Environment Federation
WMO	World Meteorological Organization
WQCB	Water Quality Control Board
WRP	water recycling plant
WSAA	Water Services Association of Australia
WTP	water treatment plant
WUCA	Water Utility Climate Alliance
WWTP	wastewater treatment plant
W/WW	water and wastewater

Foreword

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

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- Definition of and addressing emerging contaminants
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- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

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This report is designed to help water resources managers understand, assess, and appropriately include the impacts of climate change in their decisions without getting bogged down. In addition, this report explicitly points out how a reclaimed water program can be one of the best climate preparation tools because of its climate-independent nature and its ability to maximize the use of current and future water resources. The report is based on case studies of three utilities representing a broad range of climate change planning needs: the Miami-Dade Water and Sewer Department, the City of Phoenix Water Services Department, and the Inland Empire Utilities Agency.

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This project was funded by the WateReuse Research Foundation in cooperation with the Bureau of Reclamation and the California Energy Commission.

This study would not have been possible without the insights, efforts, and dedication of many individuals and organizations. These include the members of the research team and PAC members (as identified below); the WateReuse Research Foundation's project manager, Caroline Sherony; many key individuals at the participating utilities and related organizations; and the outstanding editorial and production staff at Stratus Consulting (including Diane Callow, Mary Kozyra, and Erin Miles).

The research team would like to thank the WateReuse Research Foundation for funding this applied research project, as well as the following organizations for their in-kind contributions: the Inland Empire Utilities Agency (CA), the Miami-Dade Water and Sewer Department (FL), and the City of Phoenix Water Services Department (AZ).

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Executive Summary

Water resource managers can find themselves overwhelmed when the unknowns of climate change are added to the list of uncertainties they face when planning for the future. This primer is designed to help water resources managers understand, assess, and appropriately include the impacts of climate change in their decisions without getting bogged down. In addition, this report explicitly points out how a reclaimed water program can be one of the best climate preparation tools because of its climate-independent nature and its ability to maximize the use of current and future water resources. The report is based on our case study of three utilities representing a broad range of climate change planning needs: the Miami-Dade Water and Sewer Department, the City of Phoenix Water Services Department, and the Inland Empire Utilities Agency.

Part I of this report lays out a framework designed to make it easy for water resource managers to include climate change in both day-to-day and long-term decision-making.

- The climate change planning framework begins with overview of the basic climate change information necessary to address the issue. This includes a short primer on climate science, an overview of the important climate players, and a description, with links for more detailed information, of the most likely changes in temperature and precipitation for each region of the United States.
- The second element of the planning framework provides tools for turning the most likely potential changes in temperature and precipitation in your region into potential impacts on your utility. These tools include a series of flow charts and tables that identify how specific combinations of changes in temperature and precipitation (e.g., warmer and shorter winters) may impact your utility. For example, implications of warmer and shorter winters may be more rain and less snow, earlier spring melt and runoff, both altered recharge of groundwater aquifers and altered summer and fall base flows in surface waters, and the possible need for new sources of supply to meet peak demands in summer and fall.
- The third element provides several straightforward techniques for characterizing the probable impacts of climate change in order to identify the specific implications of climate change that are likely to be of significant concern for your utility. To follow the warmer and shorter winter example, if your utility has a sole source groundwater supply and that supply is already near capacity, then the potential reduction in recharge that is due to climate change may represent a tipping point. This section also provides an overview of climate modeling and downscaling.
- The fourth element of the climate planning framework discusses strategies for adapting and preparing for climate changes. This section provides both ideas for building overall utility resilience (e.g., identifying no-regrets options and developing flexibility) and examples of specific adaptations. This section also discusses the significant role that reuse can play in preparing for climate change, including supplementing potable supplies, instream flow augmentation, aquifer recharge augmentation, coastal groundwater injection for saltwater barriers, wetlands creation or enhancement, fire suppression and control, and agricultural and other outdoor

irrigation needs. To follow our example one more time, the need for a new supply source due to warmer and shorter winters may be the catalyst for building a reclaimed water program. Part I concludes with a discussion of the vital role of coordination and communication.

In Part II we present an overview of the three case studies using the framework provided in Part I. This is designed both to provide examples and to illustrate the practicality of the planning framework. Because each of the three case study utilities faces both distinct climate challenges and a distinct political climate, the case studies provide a wide range of examples of how the developed framework can be used to include climate in utility planning, and the potential role of reuse. The complete case studies are presented in the Appendices.

Part III provides a more rigorous technical discussion of specific issues and tools presented in Part I. This is done to keep Part I easily readable while still providing information in depth. Part III includes a technical presentation of climate science and global climate models, global climate model downscaling, high-probability climate changes, tools for identifying climate change impacts on utilities, tools for identifying potential risks and vulnerabilities, sea-level rise, and an overview of common questions and misperceptions.

In sum, this document is presented to the water resource manager as a pragmatic tool to make it straightforward to include potential changes in climate in utility planning, as well as to illustrate the significant role of reclaimed water in preparing for these changes. This does not mean that the document will provide you with straightforward answers. Changes in temperatures and precipitation, increasing incidences and magnitudes of extremes events, and the exact implications of these changes for your utility are unknown. Although we discuss this and show how to identify the sensitivity of your plans to these unknowns, it will still be necessary for you, as you address potential changes in water resource management that are due to changes in climate, to continually review and update your climate change information and to identify where your utility is vulnerable to the unfolding changes in climate, and the role of a reclaimed water program.

APPENDIX E:
Implications of Future Water Supply Sources on Energy Demands

Implications of Future Water Supply Sources for Energy Demands

About the WateReuse Research Foundation

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

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

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

Implications of Future Water Supply Sources for Energy Demands

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California Energy Commission
Canada Mortgage and Housing Corporation
Bureau of Reclamation

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Disclaimer

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Acronyms

AwwaRF	American Water Works Association Research Foundation (now the Water Research Foundation)
BOD	biochemical oxygen demand
$CO_{2\text{-}eq}$	carbon dioxide equivalents
eGRID	Emissions and Generation Resource Integrated Database
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ICLEI	International Council for Local Environmental Initiatives
IPCC	Intergovernmental Panel on Climate Change
$kWh_{\text{-}eq}$	kilowatt-hour equivalents
MF	microfiltration
$MWh_{\text{-}eq}$	megawatt-hour equivalents
NPDES	National Pollutant Discharge Elimination System
PAC	Project Advisory Committee
ppt	parts per thousand
RAC	Research Advisory Committee
RO	reverse osmosis
SCVWD	Santa Clara Valley Water District
UF	ultrafiltration
UV	ultraviolet
VBA	Visual Basic for Applications
WTP	water treatment plant
WESim	Water–Energy Simulator

Foreword

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Water management decisions can have significant energy impacts. Water use requires energy in all phases, from collection to treatment to distribution to use to wastewater treatment. Multiple factors will influence the energy intensity of the water sector in the near future: climate change will affect water supply, quality, and demand, potentially creating a need for new water supply options; population growth, water use patterns, technology, and price all affect water demand; and emerging contaminants may require more energy-intensive treatment technologies. The Water-Energy Simulator (WESim) is an easy-to-use analytical tool that can be applied by water agencies, municipalities, and decision makers to evaluate the energy and greenhouse gas implications of water management decisions.

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Executive Summary

Water provision and use requires energy in all phases. As water is taken from a source and delivered to a community, gravity may be sufficient; but in many cases, water must be pumped from groundwater wells or over long distances and steep terrain. Water must then be treated to drinking water standards through a variety of processes that require energy, including filtration, sedimentation, and disinfection. Treated water is then delivered to the tap, either by gravity or by additional pumping. Even more energy is used in homes, businesses, and institutions to heat, cool, purify, and pump water. Water that is used indoors must then be returned, and in some cases pumped, to a wastewater treatment facility, where it undergoes further processing, also requiring energy. Treated wastewater then either is returned to the environment by gravity or pumping or undergoes additional processing and is reused.

Multiple factors will influence the energy intensity of the water sector in the near future. Climate change will affect water supply, quality, and demand, potentially creating a need for new supply and treatment options. Population growth, water use patterns, technology, and price affect future water demand. In addition, emerging contaminants may require more energy-intensive treatment technologies. Yet water managers are also faced with rising energy costs and limits on greenhouse gas emissions. These trends highlight the need for a clear and consistent methodology for evaluating the energy and greenhouse gas implications of water management decisions.

The Water-Energy Simulator (WESim) is an easy-to-use analytical tool for evaluating the energy and greenhouse gas implications of water management decisions. The tool is suitable for individual water utilities and groups of water utilities, as well as policy and decision makers. The model has been designed to allow the user to input actual operating data for water and energy use, as this will allow an analysis that better reflects operating conditions. However, defaults for the energy requirements of various components of the water and wastewater system are also provided.

Chapter 1

Introduction

1.1 Background

Water provision and use require energy in all phases, from extraction to treatment to delivery to use, and finally to the treatment and discharge of wastewater. First, water is taken from a source and delivered to a community. In some cases, the force of gravity is sufficient; but in many cases, water must be pumped from groundwater wells or over long distances and steep terrain. Water must then be treated to drinking water standards through a variety of processes that require energy, including filtration, sedimentation, and disinfection. Treated water is then delivered to the tap, either by gravity or with additional pumping. Even more energy is used in homes, businesses, and institutions to heat, cool, purify, and pump water. Water that is used indoors must then be returned, and in some cases pumped, to a wastewater treatment facility, where it undergoes further processing that requires energy. Treated wastewater then either is returned to the environment by gravity or pumping or undergoes additional processing and is reused.

Many factors will influence the energy intensity of the water sector in the future. Continued population growth will make meeting water demands increasingly difficult over the coming years. Between 2000 and 2030, the U.S. population is projected to increase by 30%, with much of this growth concentrated in water-scarce regions in the Southwest and Florida (U.S. Census Bureau, 2004). Water scarcity has been an ongoing concern in much of the southwestern United States, but even regions not traditionally subject to drought are facing water supply constraints. In Georgia, for example, 60% of the counties were under severe drought conditions in July 2008 (Stooksbury, 2008). In 2003, the U.S. Government Accountability Office sent a survey to water managers in all 50 states. Of the 47 states that responded, those in 36 states anticipated water shortages by 2013 under normal, nondrought conditions. Respondents in 46 states said they would be faced with shortages during a drought (GAO, 2003). Because traditional supplies in many of these regions are already overallocated, water managers are pursuing other supply and demand management options.

Climate change will further exacerbate these problems. Climate change is causing significant changes in water resources and coastal ocean conditions, ultimately affecting the supply of, and demand for, water resources. According to the Intergovernmental Panel on Climate Change (IPCC), “Increases in average atmospheric temperature accelerate the rate of evaporation and demand for cooling water in human settlements, thereby increasing overall water demand, while simultaneously either increasing or decreasing water supplies (depending on whether precipitation increases or decreases and whether additional supply, if any, can be captured or simply runs off and is lost)” (IPCC, 2001). In addition, rising sea levels exacerbate seawater intrusion problems in coastal aquifers and rivers that communities depend on for water.

To meet future needs, water managers are considering a range of water supply options, from traditional surface and groundwater sources to alternatives such as recycled water, water conservation and efficiency, stormwater capture, brackish and impaired groundwater desalination, and seawater desalination. The energy intensity of these supply options,

however, varies widely. More energy-intensive options include seawater desalination and interbasin transfers, whereas recycled water and conjunctive use are often less energy intensive. Energy-intensity estimates are highly site-specific, highlighting the need for water managers to be able to quantify and assess the energy impacts of supply sources available in their region.

Furthermore, new water treatment techniques have additional possible implications for energy demand. Stricter water-quality regulations and emerging contaminants are forcing agencies to install advanced treatment options such as ultraviolet radiation, ozone disinfection, and reverse osmosis. The differences between energy use by traditional and new treatment techniques can be significant. For example, ozone disinfection effectively kills viruses and bacteria and reduces disinfection byproducts but may use 40 times more energy than traditional disinfection methods such as chlorination (PG&E, 2006).

At the same time, water managers are faced with rising energy costs. The EPA estimates that energy costs associated with treating water and wastewater services total $4 billion every year (EPA, 2011a). Electricity prices have risen by nearly 20% (EIA, 2010a) over the last decade and are expected to continue to rise. Rising energy prices, coupled with the pursuit of more energy-intensive water management options, suggest that energy costs will increase dramatically and will represent an even larger percentage of agency expenditures.

Concerns about climate change are also prompting local, state, and federal agencies to identify the most effective and efficient ways of reducing energy use and greenhouse gas emissions. Some agencies are voluntarily setting emissions reduction targets in response to growing concern about the potential impacts of climate change on water resources. However, as greenhouse gas emission policies emerge, such as California's Global Warming Solutions Act (Assembly Bill 32), water managers may be forced to implement practices that reduce these emissions. The water sector can work to meet these targets through a variety of means, including implementing water conservation and efficiency measures; optimizing the efficiency of existing systems; and increasing renewable energy generation with wastewater biogas or wind and solar power. In addition, the water sector can develop less energy-intensive local sources, such as recycled water.

Water managers face increasing challenges and constraints in providing reliable, high-quality water supplies. Rapid population growth, emerging contaminants, rising costs, and climate change are only some of these challenges. Because water management decisions involve complex and sometimes conflicting considerations, new tools are needed that provide water managers and decision makers with useful information and that can facilitate quantification of alternative scenarios to aid in decision support. The Water-Energy Simulator (WESim) can help water and energy managers better understand the energy and greenhouse gas implications of their water management decisions and thereby inform the decision-making process.

1.2 Project Objectives

The Water-Energy Simulator (WESim) is an easy-to-use analytical tool that allows users to evaluate the energy and greenhouse gas implications of population growth, the impact of climate change, the development of alternative water and energy sources, and water treatment improvements resulting from stricter water-quality guidelines and emerging contaminants. This tool is suitable for individual water utilities and groups of water utilities, as well as policy and decision makers. This report provides background information on the model,

including its basic form and structure. A detailed user guide for WESim is included as a companion to this report.

WESim provides a common framework for users to explore alternative scenarios. For example, users can compare the energy and greenhouse gas implications of using recycled water versus seawater desalination. Alternatively, users can explore the implications of installing ozone disinfection at a water treatment facility or biogas recovery at a wastewater treatment facility. A user might evaluate ways to offset energy use and greenhouse gas emissions by installing renewable energy generation or investing in water conservation and efficiency.

The model has been designed to allow the user to input actual operating data for water and energy use, as this will allow an analysis that better reflects operating conditions. However, we recognize that not all users will have this information. To facilitate use of the model, we provide defaults for the energy requirements of various components of the water and wastewater system. Detail on the defaults can be found in Chapter 4.

Chapter 2

Literature Review

The water sector is a major user of energy, although the overall energy requirements of the water and wastewater sector remain largely unknown. Among the earliest and most commonly cited reports is an EPRI-funded study (Burton, 1996) that estimates that capturing and treating surface water requires an average of around 1400 kWh per million gallons, which is equivalent to 0.37 kWh per cubic meter (kWh/m^3). Groundwater supplies require slightly more energy on average, or around 1800 kWh per million gallons (0.48 kWh/m^3) (Burton, 1996). Burton reported that energy requirements for wastewater treatment vary depending on the type of treatment employed, ranging from less than 1000 kWh per million gallons (0.26 kWh/m^3) for basic treatment to more than 1900 kWh per million gallons (0.50 kWh/m^3) for advanced treatment.

Interest in the connection between water and energy is increasing, as evidenced by a growing number of studies conducted in recent years on the energy requirements for water and wastewater systems. These studies have been conducted at the facility, agency, state, and national levels and indicate that the energy intensity of the water and wastewater sector is large and highly variable. Some of the available studies include the following:

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The majority of studies on the energy requirements of water and wastewater systems have focused on existing systems, either to describe the connection between water and energy qualitatively or to produce some quantitative estimate of energy intensity or total energy use. Few studies have taken a prospective approach, evaluating future energy requirements under a range of treatment and supply options. There are two important exceptions. In its 2002 report, *Water and Sustainability: U.S. Electricity Consumption for Water Supply & Treatment— The Next Half Century*, EPRI estimates that the electricity consumption of public and private water and wastewater systems was 123 billion kWh per year in 2000 and is expected to grow to more than 210 billion kWh per year by 2050. This estimate is based on population growth only; the authors assume that the energy intensity for water supply will remain constant, as will per capita water use. Thus, the electricity requirements increase in proportion to projected population growth. This study provides a good first-order estimate, but the reality is likely to be somewhat more complicated. On one hand, water conservation and efficiency are driving down per capita use, particularly in the West (Cohen, 2011). On the other hand, many water suppliers are shifting toward more energy-intensive treatment technologies and marginal supply sources.

A more recent report by Kenway et al. (2008) evaluates current and future energy requirements for the provision of water and wastewater services and residential end use in 10 cities in Australia and New Zealand. The study estimates that the amount of energy required to deliver water services in 2030 will grow by up to more than 300% from 2006/2007 levels. Kenway et al.'s analysis differs from previous studies in two important ways. First, it includes residential end-use energy (although it leaves out commercial and industrial end use

energy). Second, it uses scenarios to explore alternative water futures, integrating assumptions about water demand, population growth, and various water sources (40% desalination, 40% reuse and 20% new sources, and 100% desalination). The study assumes that the energy intensity of existing sources will remain constant, and therefore it does not explore how stricter water quality regulations may affect future energy use.

Chapter 3

Model Overview

3.1 Analytical Approach

WESim uses a basic analytical approach developed by Dr. Robert Wilkinson (2000) and refined and improved upon by a number of experts. This approach divides the water cycle into the stages shown in Figure 3.1. WESim groups facilities into the following categories:

- *Source extraction* refers to the extraction of water from its source to the surface of the Earth. Energy requirements for water source extraction depend upon the location of the water relative to the surface and the method of extraction. Using this definition, the energy intensity of water supply for water that is already at the surface, e.g., seawater, recycled water, or river water, is zero.
- *Water conveyance* refers to the transport of *untreated* water through aqueducts, canals, and pipelines from its source to a water treatment facility or directly to an end user, if the end user uses raw water. Energy requirements for conveyance depend primarily on the distance and net elevation through which it is pumped, as well as pump efficiency.
- *Water treatment* refers to processes and technologies that treat water prior to its distribution to homes and businesses. The energy requirements for treatment depend upon the quality of the source water and the technology employed to treat it. For recycled water, the energy requirements for treatment include the incremental treatment required to bring treated wastewater to recycled water standards. The energy intensity of recycled water treatment depends upon the level of treatment required prior to discharge and the additional treatment required to bring it to the appropriate standard for the intended customer.
- *Water distribution* refers to the transport of treated water (both potable and nonpotable) to the customer. As with conveyance, the energy intensity of distribution depends largely on the distance and elevation through which water is pumped, as well as pump efficiency.
- *Customer end use* of water refers to the multitude of ways that water is used in residential, commercial, industrial, institutional, and agricultural settings, which include personal hygiene, dish and clothes washing, landscape and crop irrigation, process water, and equipment cooling. Energy use associated with customer end use is typically associated with heating, cooling, water treatment (e.g., filtering and softening), circulation, and supplemental pressurization in high-rises.
- *Wastewater collection* refers to the movement of untreated wastewater from the end user to a wastewater treatment facility. The energy requirements for wastewater collection depend upon local geography and pump efficiency.
- *Wastewater treatment* refers to the application of biological, physical, and/or chemical processes to bring wastewater to discharge standards. The energy requirements for wastewater treatment depend on the level of treatment and, because wastewater must be pumped throughout the treatment facility, on pump efficiency.

- *Wastewater discharge* refers to the movement of treated wastewater from the wastewater treatment facility to the receiving waters. Energy requirements for wastewater discharge depend upon local geography and pump efficiency.

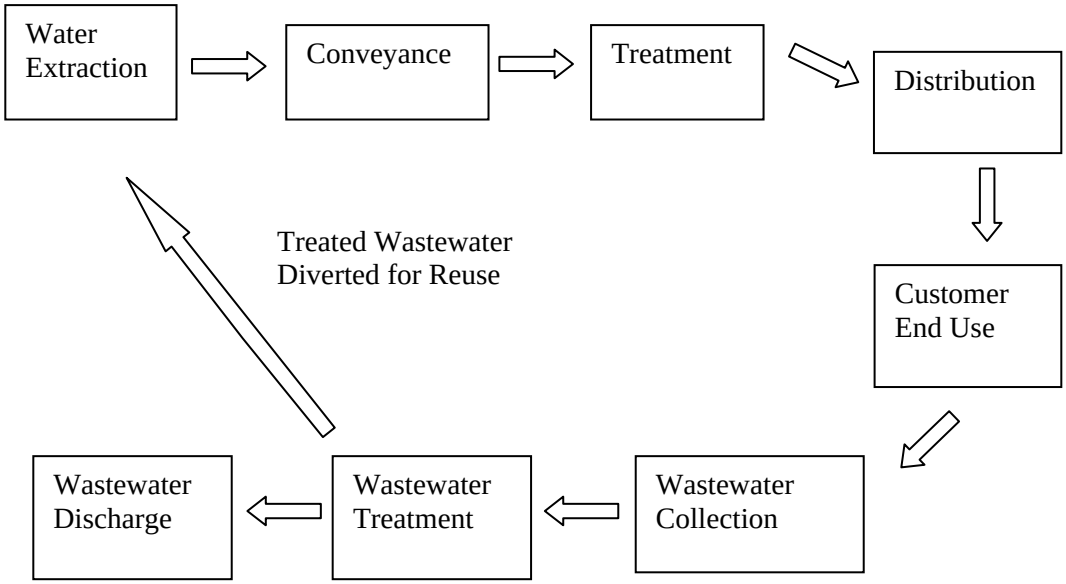

Figure 3.1. Flow diagram of the water and wastewater system.

Source: This schematic and method are based on Wilkinson (2000) with refinements by California Energy Commission staff and others.

Although these definitions set forth clear boundaries between the system components, in reality, these boundaries can be fuzzy. For example, an agency might be pumping high-quality groundwater from a well and adding a small amount of chlorine at the well for disinfection prior to distribution to customers. In this case, the energy requirements for groundwater pumping and chlorine injection are likely captured by a single electricity meter and there is no way to distinguish between the energy requirements for source water extraction and treatment. Using this analytical framework, the user will have to classify the energy requirements as *either* source extraction or treatment. Either classification is acceptable; however, the user must be sure not to include the energy requirements as *both* source extraction and treatment, to avoid double counting.

Although perhaps it is not intuitive, recycled water can easily fit within the framework shown in Figure 3.1. For recycled water, the “source” is treated wastewater. As described previously, source water extraction is the energy required to bring recycled water to the surface. Because recycled water is already at the surface, the energy requirements for extraction are effectively zero. (The issue of indirect potable reuse will be discussed separately later.)

Conveyance is the movement of raw water from the source to the treatment plant. For recycled water, the source is the wastewater treatment facility. In many cases, recycled water

treatment occurs at the wastewater treatment facility, and thus no conveyance is required. In a limited number of cases, however, treated wastewater may be transported to another facility to undergo treatment to bring it to recycled water standards. In this case, the movement of treated wastewater from the wastewater treatment facility to the recycled water treatment facility would be classified as conveyance.

Recycled water treatment refers to the additional treatment required to bring treated wastewater to reuse standards. In many cases, wastewater is treated to secondary standards before it is discharged into the environment. Treatment for reuse is the additional treatment required to bring the secondary-treated wastewater to the appropriate standard for reuse. In some cases, however, wastewater is already treated to such a high degree before discharge to the environment that little to no additional treatment is required. Treatment requirements for recycled water might even be less than those for wastewater discharge, suggesting possible net energy savings with reuse. For example, nutrient removal, an energy-intensive process, might be required for wastewater discharge but not for reuse on landscapes in some areas.

Distribution of recycled water refers to the movement of the recycled water from the water recycling facility to the end user. Currently, recycled water is distributed to customers through a separate distribution system. With indirect potable reuse, recycled water is treated to potable standards and then used to recharge groundwater or surface reservoirs. In this case, distribution refers to the transport of treated recycled water from the recycled water facility to the surface or groundwater reservoir.

3.2 Model Structure

WESim uses scenario-based planning to model how changes to water systems will affect energy use and greenhouse gas emissions. WESim uses the concepts of *facilities*, water *systems*, and *scenarios* to model these changes. A facility can include a single well or treatment plant or a group of facilities that serve a similar purpose, such as a well field. For each facility, the user enters the following information:

(1) the facility name;
(2) its category (e.g., extraction, treatment, distribution);
(3) water flow through the facility;
(4) the energy use of the facility; and
(5) the source of energy to power the facility.

Because a single facility may be powered by multiple energy sources, such as electricity plus a natural-gas-powered backup generator, WESim allows the user to enter up to five different energy sources for a single facility. The water system is made up of any number of these facilities. Each scenario is a description of the water system under a certain set of conditions.

For example, say a water agency extracts water from a local reservoir, provides treatment at a nearby facility, and distributes treated water to its customers. This agency also collects, treats, and discharges wastewater. The agency is considering recycling some of the wastewater to offset withdrawals from the local reservoir.

To begin with, the user first develops the Baseline Scenario. The Baseline Scenario contains all of the existing water system facilities, including the pumps to convey raw water and wastewater to the treatment plant, the water and wastewater treatment plant, and the booster pumps to distribute treated water to the customers. For each facility, the user enters

information about the water flow through the facility, its energy use, and the source of energy.

The user can then develop a second scenario, for example, “Baseline with Recycled Water.” In the second scenario, the user reduces the volume of surface water that is conveyed, treated, and distributed and the volume of wastewater that is discharged into the environment. The user then adds all of the new recycling facilities. Once these changes have been made, the user can view the model output and compare the overall energy consumption and greenhouse gas emission between the “Baseline” and “Baseline with Recycled Water” scenarios. This example is illustrated in Figure 3.2.

Scenarios:	**Baseline**	**Baseline with Water Recycling**
System	Source extraction Local surface water	Source extraction **Local surface water** *Recycled water*
	Water conveyance Raw water pumps	Water conveyance **Raw water pumps**
	Water treatment Treatment plant	Water treatment **Treatment plant** *Recycled water treatment*
	Water distribution Booster stations	Water distribution **Booster stations** *Recycled water booster stations*
	Wastewater conveyance Sewer booster stations	Wastewater conveyance Sewer booster stations
	Wastewater treatment Wastewater plant	Wastewater treatment Wastewater plant
	Wastewater discharge Gravity-fed	Wastewater discharge **Gravity-fed**
	End use Commercial Industrial Residential	End use Commercial Industrial Residential

Figure 3.2. Example of a simple simulation.

Note: The new components are shown in *italics*, and the modified components are shown in **bold**.

3.3 Energy Use and Greenhouse Gas Emission Calculations

Water and wastewater facilities commonly use a combination of energy sources, e.g., electricity, natural gas, diesel, and biogas produced on site. Some of these energy sources (natural gas, diesel, and biogas) are primary energy sources, meaning that the raw fuel is consumed on site to produce heat or electricity. Electricity, on the other hand, is a secondary energy source because it is the product of raw fuel burned elsewhere. Because different energy sources are measured in different units and have different associated efficiency losses, calculating total facility energy use and greenhouse gas emission requires converting the diverse energy sources into common units. Sections 3.3.1, 3.3.2, and 3.3.3 describe the methodology for calculating total energy use and greenhouse gas emission.

3.3.1. Determining Total Energy Use

British thermal units (Btu) and joules (J) are units of energy that are often used for comparing total energy used at a facility. Once all energy use is converted to a common unit, it can be summed to find total site energy use. However, even after conversion to common energy units, primary and secondary energy sources are still not directly comparable because there are different efficiency and transmission and distribution losses associated with them. For example, some electricity is lost during transmission and distribution from a power plant to homes and businesses. To accurately account for all energy use associated with a particular facility, the various types of energy used on site must be converted into *source energy*. Source energy is the total amount of raw fuel that is consumed to operate the facility (including fuel used to produce electricity off site). This is done by multiplying site energy by the appropriate site–source ratio for each energy type.

WESim reports both site and source energy for each of the scenarios. Source energy allows a more accurate comparison among the alternative scenarios, whereas the site energy puts the energy in units more familiar to the facility operator. For site energy, WESim reports the total use of electricity, natural gas, biogas, diesel fuel, propane, etc. for each scenario. These data are provided in tabular form, allowing the user to combine the output with current and projected energy prices to evaluate trends over time.

To convert from site to source energy, the following three-step methodology is integrated into WESim:

1. Calculate total site energy for each fuel.

To determine the total energy use of a water or wastewater facility, energy from all of the potentially diverse energy sources is converted into common units. British thermal units (Btu) or joules (J) are often used as a common unit for calculating total energy use. To convert into common energy units, all site energy consumed (both primary and secondary) is multiplied by the appropriate conversion factors. The heat content of a number of primary and secondary energy sources is provided in Table 3.1. These figures reflect average energy content for fuels consumed in the United States, although they are generally applicable elsewhere.

Table 3.1. Heat Content of Common Fuels

Energy Unit	Heat Content	
	British Thermal Unit (Btu)	Kilojoule (kJ)
1 gallon of gasoline	125,071	131,950
1 gallon of diesel fuel	138,690	146,318
1 gallon of residual fuel oil	149,690	157,923
1 cubic foot of natural gas	1,027	1,083
1 gallon of propane	91,333	96,357
1 kilowatt-hour of electricity	3,412	3,600
1 cubic foot of biogas	600	633

Note: Heat content of natural gas is based on data for U.S. consumption in 2009.

Sources: EIA, 2010b; EPA/CHPP, 2007.

2. Convert site energy into source energy.

The reported site energy use (energy use as shown on utility bills) is then converted into source energy using source–site ratios. Source–site ratios for various fuel types are shown in Table 3.2, along with an explanation of losses accounted for in the ratio. The source–site ratios account for losses that occur in the distribution, storage, and dispensing of a primary fuel, as well as production efficiency losses at power plants.

3. Sum the source energy for the various fuels consumed.

Once all of the fuels have been converted to source energy, they can then be added together to produce a total source energy for each scenario. Putting all of the various energy sources into a single unit allows more accurate comparison among the various scenarios under consideration. For source energy, WESim uses Btu and J. Because most energy managers are familiar with units of electricity, WESim converts all of the source energy into site energy and reports in units of kilowatt-hour equivalents (kWh_{-eq}) and megawatt-hour equivalents (MWh_{-eq}), which represents the total electricity that would have been generated if all of the fuels had been used to produce electricity.

Table 3.2. Source–Site Ratios by Fuel Type

Fuel Type	Source–Site Ratio	Losses Accounted for in Ratio
Electricity (purchased from utility)	3.34	Production losses, plus transmission and distribution losses
Electricity (on-site solar or wind installation)	1.0	No production losses because electricity is derived from the sun or wind; no transmission or distribution losses because it is converted on site
Natural gas	1.047	Losses associated with pipeline transmission and distribution to consumer
Fuel oil (1, 2, 4, 5, 6, diesel, kerosene)	1.01	Losses associated with distribution, storage, and dispensing
Propane and liquid propane	1.01	Losses associated with distribution, storage, and dispensing

Source: EPA, 2011b.

3.3.2 Greenhouse Gas Emission Factors

As concerns about climate change intensify, many individuals and governments are seeking ways to reduce greenhouse gas emissions. WESim reports greenhouse gas emissions for each scenario, thereby providing another metric by which to evaluate water management alternatives. Within WESim, the user enters every energy source that powers the water and wastewater system, including electricity purchased from a third party and fuels used on site to produce electricity, heat, or motive power. For each energy source, the user also enters the greenhouse gas emission factor associated with each fuel. Emission factors represent the amount of greenhouse gas emissions per unit of fuel or energy consumed. Some emission factors are programmed into the model. However, the model also allows the user to enter custom emission factors to account for alternative energy sources and any changes in the emission factors over time. This is especially important for the electricity factors, which will change as energy providers alter the fuel mix powering the electricity grid.

3.3.2.1 Emission Factors for Electricity

Greenhouse gas emissions associated with electricity use are driven by the type of fuels used to generate the electricity, which varies regionally and temporally. Additionally, as energy utilities alter their fuel mix to meet renewable portfolio standards and goals and in response to changes in the availability and cost of energy sources, the greenhouse gas emission factors will change. Therefore, emission factors that are specific to the user's area, and that correspond for the year for which he or she is reporting data, should be used whenever possible.

Electricity emission data can be accessed from a variety of sources. These data are typically either regional or utility-specific values. When possible, utility-specific values should be used, because the regional data do not capture local variability in emissions factors. Users can contact their local electricity providers to obtain appropriate emissions factors. Third-party verified emissions factors for electricity providers that are members of the California Climate Action Registry can be found in Table G.6 in CARB (2010).

It is not yet standard for energy utilities to calculate and verify their emission factors. In the absence of these data, regional electricity emission factors may be needed. Regional estimates can be found at the following locations:

- The EPA produces the Emissions and Generation Resource Integrated Database (eGRID), a comprehensive data source for electricity emission factors for 26 subregions across the United States. These data are updated periodically to better reflect changes in emissions from the U.S. electricity grid. The newest version, released in February 2011, provides data for the year 2007. The eGrid data can be found in EPA, 2011c.
- For Canada, province-level data are available in Environment Canada, 2010a.
- For all other countries, emission factors for electricity production can be found in IEA, 2010.

Table 3.3. Greenhouse Gas Emission Factors for Various Primary Fuels and for Electricity

Fuel Type	Energy Unit	Emissions Factors (kg/energy unit)		
		Carbon Dioxide (CO_2)	Methane (CH_4)	Nitrous Oxide (N_2O)
Electricity (avg. U.S. grid)	kWh	0.588	1.14×10^{-5}	8.93×10^{-6}
Electricity (avg. Canadian grid)	kWh	0.206	9.00×10^{-6}	4.00×10^{-6}
Solar	kWh	0	0	0
On-site cogeneration	ft^3 or m^3	0	0	0
Gasoline	gal	8.780	1.40×10^{-3}	1.00×10^{-4}
Gasoline (Canadian metric)	L	2.289	1.2×10^{-4}	1.6×10^{-4}
Diesel fuel	gal	10.21	1.50×10^{-3}	1.00×10^{-4}
Diesel fuel (Canadian metric)	L	2.663	1.33×10^{-4}	4.00×10^{-4}
Natural gas (U.S.)	therm	5.302	1.00×10^{-4}	1.00×10^{-5}
Natural gas (Canadian metric)	m^3	1.881	3.70×10^{-5}	3.5×10^{-5}

Notes: Natural gas emissions for Canada were based on average of Canadian provinces (except Northwest Territories) in Environment Canada, 2010b. Electricity emissions factors are based on average grid in the United States and Canada in 2007 from Table A1 in EPA, 2008 and Environment Canada, 2010a.

Sources: Tables G1, G11, and G19 in CARB, 2010; Table A1 in EPA, 2008; Environment Canada, 2010a, 2010b.

3.3.2.2 Emissions Factors for Various Fuels

Greenhouse gas emission factors for other fuels are much less variable than for electricity. As a result, default values are provided in WESim, which are shown in Table 3.3. In some cases, as with natural gas, there is regional variation. WESim allows the user to add additional energy sources and emission factors as needed. Additional factors can be found in Environment Canada (2010) and California Air Resources Board (2010).

3.3.2.3 Biogas Cogeneration

The current widely accepted greenhouse gas emissions inventory guidelines consider biogenic sources, including biogas, to be carbon-neutral (Cooper, 2010; Gomez et al., 2006; ICLEI, 2010). The EPA's decision not to include biogenic sources may be temporary. Currently, the EPA has proposed to defer emissions from biogenic sources for three years, during which time the EPA will further study biogenic sources of CO_2 (EPA, 2011d). Additionally, regulatory greenhouse gas reporting requirements may vary by location. Within WESim, the default value for biogas used by water and wastewater utilities is zero. However, WESim is designed so that the user can adjust the emission factors in response to changing conditions. We recommend that the user check back with the EPA once this issue is resolved.

3.3.2.4 Non-Energy-Related Greenhouse Gas Emissions Associated with Wastewater Treatment Facilities

Wastewater treatment processes can emit a range of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CH_4 and N_2O can be produced by wastewater treatment facilities through a variety of processes. CH_4 can be produced through incomplete combustion of digester gas at a centralized treatment plant with anaerobic digestion of biosolids and through anaerobic and facultative treatment lagoons. N_2O can be

produced through the nitrification/denitrification process, and from effluent discharge to receiving aquatic environments.

In both the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the ICLEI Local Government Operations Protocol (ICLEI, 2010), CO_2 produced by wastewater treatment is considered biogenic, and therefore is not included. Because of the higher global warming potentials of these greenhouse gases and because they would not be produced under natural conditions, CH_4 and N_2O produced by wastewater facilities are included in greenhouse gas inventories conducted according to these protocols. Because the focus of WESim is on energy-related greenhouse gas emissions, these estimates are not included in the model. However, the user can calculate these emissions separately and add them to the energy-related greenhouse gas emissions produced by WESim.

3.3.3 Determining Greenhouse Gas Emissions

Within WESim, greenhouse gas emissions are calculated by multiplying the user-defined emission factors by the source energy. For all primary fuels, e.g., natural gas, diesel, propane, consumed onsite, this requires converting the reported site energy to source energy using the source–site ratios in Table 3.2. For example, a facility uses 10,000 therms of natural gas. Therefore the site energy use is 10,000 therms. Using a source–site ratio of 1.047 to account for losses associated with pipeline transmission and distribution to customers, the source energy use for that facility is 10,470 therms. Because natural gas combustion emits 5.30 kg CO_2 per therm, the CO_2 emissions for this facility is 55,490 kg CO_2.

Typically greenhouse gas emissions from electricity are expressed in units of CO_2 per kWh generated. For example, the Emissions and Generation Resource Integrated Database (eGRID) provides data on various air emissions, including greenhouse gases, associated with electric power generated in the United States. eGRID emission factors are based on electricity generated, not electricity delivered. To account for line losses, WESim applies grid loss factors to the reported electricity use. Table 3.4 contains eGRID gross grid loss factors for various regions in the United States and in Canada. WESim uses average grid losses of 6.16% and 8% for users in the United States and Canada, respectively. For example, a facility uses 10,000 kWh of electricity. Using an average grid loss of 8%, total electricity use is 10,800 kWh. If the electricity emission factor is 0.588 kg CO_2 per kWh, then the CO_2 emissions for this facility is 6350 kg CO_2.

Table 3.4. Gross Grid Loss Factors

Region	Gross Grid Loss Factor (%)
Eastern grid	6.47
Western grid	4.84
Texas	6.42
Alaska	1.24
Hawaii	3.20
United States	6.16
Canada (national average)	8.00

Sources: EPA, 2010; World Bank, 2011.

Table 3.5. Global Warming Potential Values

Greenhouse Gas	Global Warming Potential
CO_2	1
CH_4	25
N_2O	298

Note: Based on 100-yr warming potential as provided in Forster et al., 2007.

Greenhouse gas emissions are reported for CO_2, CH_4, and N_2O. Total emissions are reported in units of CO_2 equivalents ($CO_{2\text{-eq}}$). The total emissions are derived by multiplying the emissions of each greenhouse gas by its global warming potential. Global warming potential values are shown in Table 3.5.

Chapter 4

Model Defaults

WESim uses scenario-based planning to model how changes to water systems will affect energy use and greenhouse gas emissions. Although users are encouraged to input actual operating data, defaults are provided in the event that the user does not have this information. The default values may also be useful for scenario planning when more detailed studies have not yet been conducted.

There are no generally accepted values for the energy intensity of water and wastewater systems, and for some processes, few data are available in the literature. More and better data are needed. To develop default values, the Pacific Institute conducted an extensive literature review of energy-intensity values for each stage of the water use cycle: water extraction, water conveyance, water treatment, water distribution, customer end use, wastewater collection, wastewater treatment, and wastewater discharge. A preliminary analysis of the data revealed significant variability among water and wastewater systems. In many cases, additional information was not available to determine the cause of this variability, e.g., the size of the facility or the various treatment processes employed. Detailed surveys of water and wastewater utilities are needed to develop more robust energy-intensity estimates. Such an effort, however, was beyond the scope of this project.

In 2007, a comprehensive study was funded by the Awwa Research Foundation (AwwaRF), the California Energy Commission, and the New York State Energy Research and Development Authority that was designed to develop an energy index for benchmarking water and wastewater utilities (AwwaRF 2007). The researchers mailed detailed surveys to water and wastewater utilities across the country in order to collect data on energy use in 2004 and on utility characteristics for water utilities serving populations of 10,000 or more and wastewater utilities with a design influent flow exceeding 1.5 MGD (5,700 m^3/d). Data were gathered from 266 wastewater treatment plants and 125 water utilities, and regression analyses were performed to test the correlation of various system parameters with energy use. For water utilities, the analysis evaluated the utility as a whole, as well as production, treatment, and distribution individually. For wastewater utilities, the analysis included collection and treatment individually. Based on our review, we determined that this was the most robust dataset available and that the regression equations developed as part of this analysis should be integrated into WESim.[1] These regression equations have also been adopted by the EPA in its benchmarking tool for water and wastewater utilities.

We did note, however, that some water treatment processes were not adequately captured in the AwwaRF study. In particular, brackish and seawater desalination were not represented among the various treatment technologies. Additionally, the sample size for utilities using ozone, UV, or membranes for disinfection was small. We supplement the information in the

[1] We noticed some inconsistencies between the calculations in the Excel spreadsheets available for download on the AwwaRF Web site and the description of the equations in the AwwaRF (2007) report. When in doubt, we matched our calculations to those in the Excel workbooks.

AwwaRF study with other values from the literature. Additional information on the model defaults for each of the water and wastewater system components is described in greater detail later.

For each default, we collected and summarized the available data and, based on these data, developed low, median, and high estimates. The low and high values represent the first and third quartiles, respectively. In some cases, there is significant variability in the available data. Within each section following, we provide as much information as is available about the primary drivers behind the range of values to guide the user in selecting the most appropriate value. Note that the defaults are meant as a guide, and users are able to enter specific data for their facilities or from other data sources.

4.1 Water Source Extraction

Water source extraction refers to the movement of water from its source to the ground surface. Subsequent pumping of raw water over land is characterized as conveyance. Energy requirements for extracting water from its source depend on the location of the water relative to the ground surface and the method of extraction. Other factors affecting energy use include pump efficiency, motor efficiency, and the volume of water pumped.

For surface water, including seawater, the energy requirements are effectively zero because the water source is already at the surface. Likewise, recycled water is already at the surface and thus the energy intensity of extraction is effectively 0 (Table 4.1).

For groundwater, the energy requirements depend upon the depth from which the water must be pumped and the pump and motor efficiency. Because pumping depth is site-specific, WESim provides a calculator to estimate average energy intensity based on depth and pump and motor efficiency. The following equation is used:

$$E = \frac{\dot{m} g h}{e} \tag{4.1}$$

where

E = Pumping energy use, in joules per second

$\dot{m}$ = Mass flux of pumped water, kg per second

g = Gravitational acceleration constant, 9.81 meters per second per second (m/s^2)

h = Height that water is lifted, or depth of the well, in meters

e = Efficiency (combined efficiency of the pump and motor), a dimensionless number.

Table 4.1. Source Extraction Energy Intensity

	Energy Intensity (kWh/MG)
Surface water	0
Groundwater	Calculated based on user-provided data on pumping depth and efficiency
Seawater	0
Recycled water	0

4.2 Water Conveyance

Water conveyance refers to the transport of water from its source to a water treatment facility. Conveyance energy requirements are dependent primarily on the distance and net elevation through which it is pumped, as well as on the efficiency of the pumps used. Other sources of variability include the type of conduit (e.g., pipeline, open channel, lined vs. unlined), rate of water leaks, seepage and evaporation, and volume of water conveyed. We discuss defaults for potable and recycled water conveyance separately.

4.2.1 Potable Water Conveyance

Our analysis reveals significant variability in the energy requirements for potable water conveyance (Figure 4.1). For local water sources, the energy intensity has a median value of 110 kWh per million gallons (0.029 kWh/m^3), with low and high values of 88 and 330 kWh per million gallons (0.023 and 0.087 kWh/m^3), respectively (GEI, 2010b; CEC, 2005; ECONorthwest, 2011; Wolff et al., 2004; CSA, 2008). For example, the San Jose Water Company, whose service area is located near the southern portion of the San Francisco Bay, provides its customers with local surface water from a reservoir in the adjacent Santa Cruz Mountains and two nearby creeks. Gravity is sufficient to convey raw water from the reservoir to the treatment plant, whereas pumps are required to convey water from the creeks to the treatment plant.

Overall, an estimated 110 kWh per million gallons (0.029 kWh/m^3) is required to convey surface water over the varied terrain (ECONorthwest, 2010). By contrast, the Contra Costa Water District, also in northern California, conveys raw surface water to retail water agencies, local raw water customers, and two treatment plants. Overall, nearly 1200 kWh per million gallons (0.32 kWh/m^3) is required to convey raw water through the 48-mile Contra Costa Canal over relatively hilly terrain (GEI, 2010b).

For imported water, the median energy intensity is 3000 kWh per million gallons (0.79 kWh/m^3), with low and high values of 1900 and 5300 kWh per million gallons (0.50 and 1.4 kWh/m^3), respectively (GEI, 2010b; ECONorthwest, 2011; GEI, 2010a; Wolff et al., 2004) (Table 4.2). The range of values for imported water is particularly high because in some systems, gravity is sufficient to move water long distances whereas in others, extensive pumping is required.

Table 4.2. Energy Intensity for Conveyance of Local and Imported Water

	Local Water	Imported Water
Low value (kWh/MG)	88	1900
Median value (kWh/MG)	110	3000
High value (kWh/MG)	330	5300
Data points	9	7

Notes: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartiles, respectively. Energy requirements for conveyance will depend, in part, on the distance pumped and change in elevation. The user is cautioned that these factors are not explicitly addressed in these values.

Data sources: Local water: CEC, 2005; CSA, 2008; ECONorthwest, 2011; GEI, 2010b; Wolff et al., 2004. Imported water: ECONorthwest, 2011; GEI, 2010a, 2010b; Wolff et al., 2004.

For example, water from the Hetch Hetchy system travels in excess of 100 miles across California's Central Valley largely by the force of gravity; energy requirements for this system are only 2 kWh per million gallons (5.3×10^{-4} kWh/m^3)(GEI 2010a). In contrast, imported water from the Sacramento-San Joaquin Delta and the Colorado River travels hundreds of miles and over steep terrain to San Diego, requiring 7500 kWh per million gallons (2.0 kWh/m^3)(GEI, 2010a).

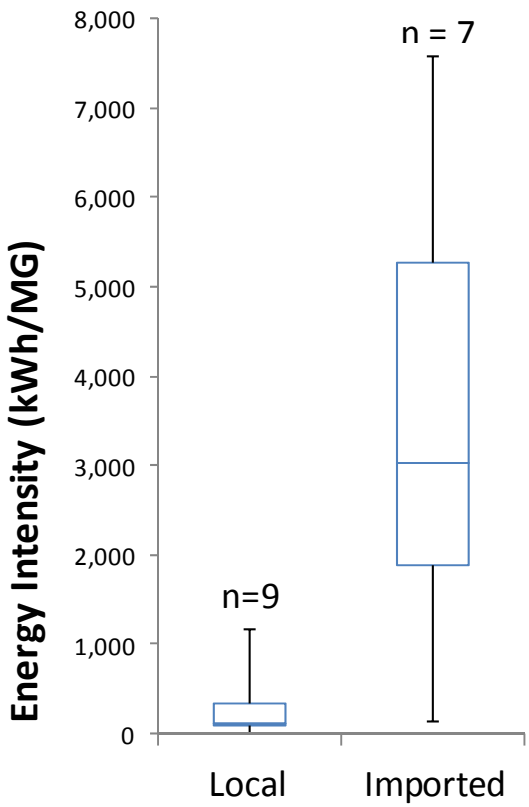

Figure 4.1. Energy intensities for conveyance of local and imported water.

Data sources: Local water: CEC, 2005; CSA, 2008; ECONorthwest, 2011; GEI, 2010b; Wolff et al., 2004. Imported water: ECONorthwest, 2011; GEI, 2010a, 2010b; Wolff et al., 2004.

Given significant variability among water systems, we supplement the data in Table 4.2 with data from the 2007 AwwaRF study. The AwwaRF study collected raw water conveyance data from 76 utilities across the United States and performed a regression analysis on various utility characteristics (AwwaRF 2007, pp. 45–46). The regression model estimated energy requirements for water conveyance based on total flow, production pump horsepower, and amount of purchased water. These parameters explained 79% of the raw water conveyance energy variability, and the model residuals were randomly distributed. The regression model is

$$EI = \exp(8.0924 + 0.6904 \ln(calc_flow) + 0.4423 \ln(raw_hp) - 0.0748 \ln(raw_p_aflow + 1)) \quad (4.2)$$

where

EI	=	Source energy intensity, in thousand Btu (kBtu) per year
calc_flow	=	Average daily total flow, in thousands of gallons per day (kgd)
raw_hp	=	Total raw water pumping horsepower, in horsepower (hp)
raw_p_aflow	=	Average daily purchased water flow, in thousand gallons per day (kgd).

WESim integrates this model into the default calculator, allowing the user to enter information on the required parameters, and performing all the necessary unit conversions. We recognize that all users will not have this information, especially for future systems, and will thus provide the model as well as the default values shown in Table 4.2.

4.2.2 Recycled Water Conveyance

As described previously, conveyance is the movement of raw water from the source to the treatment plant. In the case of recycled water, the wastewater treatment facility is the "source" of the water. In most cases, recycled water treatment will occur at the wastewater treatment facility, and thus no conveyance is required. In some cases, however, treated wastewater might be transported to another facility to undergo treatment to bring it to recycled water standards. For example, secondary effluent from the city of Los Angeles's Hyperion Treatment Plant travels about 4 miles to the Edward C. Little Water Recycling Facility in El Segundo, CA, where it undergoes additional treatment to bring it to recycled water standards. In this case, the energy intensity of conveyance includes the energy required to move the treated wastewater from the wastewater treatment facility to the recycled water treatment facility. For the model defaults, we assume that wastewater treatment and recycled water treatment occur at the same facility and that conveyance requirements are zero. We encourage users to use the default values only if the assumptions reflect their current or projected future operations.

4.3 Water Treatment

Water treatment refers to the processes and technologies that treat water to drinking water standards prior to its distribution to homes and businesses. The energy requirements for treatment depend upon the quality of the source water and the technology employed to treat that water. Treatment technology selection at a given treatment plant is based in part on the

presence of different types of regulated contaminants in the source water. When more than one technology exists that can achieve the same treatment goal, considerations such as capital and operating cost, ease of use, and reliability inform technology selection. In this section, we provide estimates for a range of water treatment processes, including chlorine disinfection, conventional treatment, and advanced treatment.

4.3.1 Chlorine Injection

In some cases, e.g., for some groundwater, water requires very little treatment to bring it to potable water standards. In these instances, only chlorine is required for disinfection. Treatment energy requirements for these systems are low. Based on four data points, we estimate that the energy intensity of chlorine disinfection has a median value of 9.5 kWh/MG (0.0025 kWh/m^3) and low and high values of 8.0 and 10 kWh/MG (0.0021 kWh and 0.0026 kWh/m^3), respectively (EPRI, 2002; PG&E, 2006; PG&E, 2007). Note that these estimates do not take into account the energy for chemical production, which would be considered in a life-cycle analysis.

4.3.2 Conventional Treatment for Drinking Water Systems

Conventional water treatment consists of coagulation, sedimentation, filtration, and disinfection (Figure 4.2). Screens that remove large debris from the raw water are typically located at the water source. The raw water is then conveyed to a treatment facility, where coagulants, such as iron or aluminum salts, are added to bind suspended particles together. The larger, heavier particles then sink to the bottom of the sedimentation vessel and are removed, a process referred to as sedimentation. The water then passes through a media filter (typically sand, gravel, or charcoal) to remove other forms of particulate matter. The water is disinfected to kill any remaining pathogens, for example, viruses and bacteria. Chlorine is the most common disinfection agent in the United States. In response to stricter water-quality regulations and emerging contaminants, however, some agencies are installing more energy-intensive disinfection options, such as ozone and microfiltration.

Energy requirements for conventional water treatment are impacted by a variety of factors, including the size of the facility, influent and effluent water quality, and the treatment technologies employed. A literature review identified 27 data points for water treatment facilities, although most studies do not collect and/or report information about these factors. Because of the high variability among treatment plants and the lack of information to identify the factors contributing to this variability, the project team found that these data are not appropriate to integrate into WESim. The AwwaRF 2007 study, however, collected water treatment energy and process data from 92 utilities across the United States. A regression analysis found that parameters related to water source and treatment processes explained 67% of the variability (AwwaRF 2007, p. 49). The model form is

$$\begin{aligned} EI = \exp(&10.8346 + 0.6100 \ln(calc_flow) - 0.0861 \ln(raw_p_aflow + 1) \\ &+ 0.1221 \ln(raw_hp + 1) + 0.7279\, treat_ox \\ &- 0.7214\, process_filtr_direct - 0.8312\, res_sand - 0.9315\, treat_iron \\ &+ 0.7946\, process_ox) \end{aligned} \tag{4.3}$$

where

EI	=	Source energy intensity, in thousand Btu (kBtu) per year
calc_flow	=	Average daily total flow, in thousand gallons per day (kgd)
raw_p_aflow	=	Average daily purchased water flow, in thousand gallons per day (kgd)
raw_hp	=	Raw water pumping horsepower, in horsepower (hp)
treat_ox	=	Presence of oxidation treatment (0 or 1)
process_filtr_direct	=	Presence of direct filtration (0 or 1)
res_sand	=	Presence of sand filtration (0 or 1)
treat_iron	=	Whether iron removal is a treatment objective (0 or 1)
process_oz	=	Presence of ozone disinfection (0 or 1).

WESim integrates this model into the default calculator, allowing the user to enter information on the required parameters.

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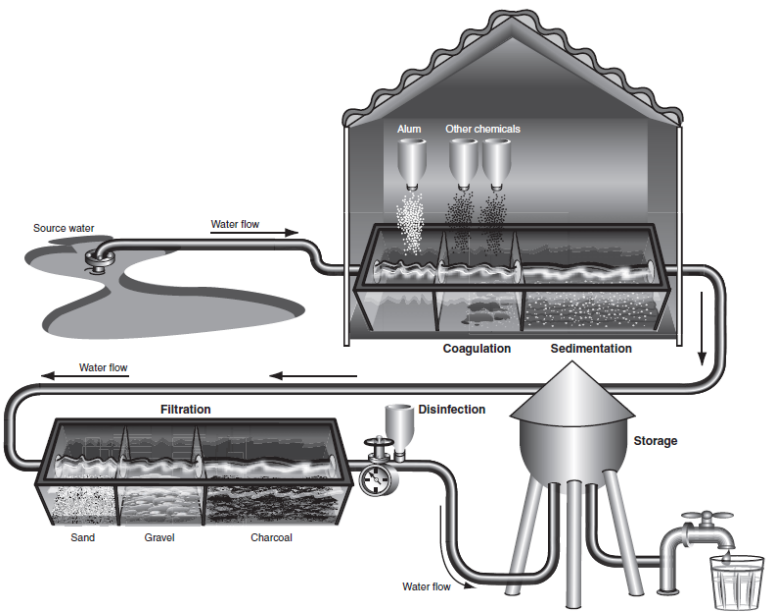

Figure 4.2. Schematic of a typical drinking water treatment system.
Source: GAO, 2011.

Table 4.3. Energy Intensity of Conventional Water Treatment by Treatment Plant Capacity

	Plant Capacity			
	Less than 1 MGD	**1–5 MGD**	**5–20 MGD**	**20+ MGD**
Low value (kWh/MG)	620	300	180	120
Median value (kWh/MG)	1500	750	560	210
High value (kWh/MG)	2000	1300	1100	2000
Data points	13	32	24	18

Note: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartiles, respectively. Treatment energy requirements generally decline as facility size increases. Even within a size category, variation in energy requirements is large and is driven by other factors, including the type of filtration and source water quality. Facilities using pressure filtration and oxidation are likely at the higher end of the range, whereas facilities using direct or sand filtration are likely at the lower end of the range.

Data source: AwwaRF, 2007.

We recognize, however, that not all users will have access to this information, especially when modeling future treatment systems. In addition, advanced treatment options, such as UV disinfection and membrane filtration, were not well represented among the water utilities surveyed. We therefore supplement the AwwaRF treatment model with a summary of the raw data collected to produce that model and data on advanced treatment options collected elsewhere (advanced treatment options are described in Section 4.3.3).

The 2007 AwwaRF study collected data on the treatment energy requirements, facility size, and treatment processes employed. Based on this data, we produced estimates for conventional treatment by facility size (Table 4.3). As expected, treatment energy requirements generally decline as the facility size increases. Even within a size category, variation in energy requirements is large and is driven by the factors identified in the regression analysis; facilities using pressure filtration and oxidation are likely at the higher end of the range, whereas facilities using direct or sand filtration are likely at the lower end of the range.

4.3.3 UV and Ozone Disinfection for Drinking Water Systems

Alternative disinfection methods, such as UV and ozone disinfection, are becoming more common in response to new drinking water contaminants, concern about disinfection byproducts, and more stringent drinking water requirements. Energy requirements for these technologies are shown in Table 4.4 and described in greater detail in the following. We note that these estimates are the best information currently available. As more and better data become available, however, the defaults within WESim will be updated.

Ozone is being applied as a disinfectant by a growing number of water agencies. Ozone, which consists of three oxygen atoms, is a powerful oxidant that can effectively destroy bacteria and viruses. Ozone is a relatively unstable gas and consequently must be generated on site using either ambient air or liquid oxygen. Generating ozone from ambient air requires more energy than if it is generated from liquid oxygen. In addition to feed gas quality, energy requirements for an ozonation system depend on the plant capacity, the operating flow rate,

and the necessary ozone dosage rate (Chang et al., 2008). Based on an extensive literature review, the median energy requirement for ozone disinfection is 160 kWh per million gallons (0.042 kWh/m^3), with low and high estimates of 120 and 440 kWh per million gallons (0.032 and 0.12 kWh/m^3), respectively (Chang et al., 2008; Mackey et al., 2001; Karns, 2004; PG&E, 2006; Elliott et al., 2003). Facilities at the higher end of the range include those that generate ozone from ambient air or that have high ozone dosage rates. Facilities at the lower end include those that generate ozone from liquid oxygen or that have low dosage rates. These estimates represent the energy requirements for ozone disinfection alone and do not include energy requirements for conventional water treatment, for example, coagulation, sedimentation, and filtration.

In response to concerns about disinfection byproducts, a growing number of water agencies are using UV radiation as a disinfectant. UV disinfection uses UV light from low- and medium-pressure lamps to damage portions of the DNA and RNA of microorganisms that regulate their ability to reproduce. Low-pressure lamps, which are generally used in small facilities, require less energy than medium-pressure lamps, which are used in larger facilities. Note that size is not the only factor that determines whether low- or medium-pressure lamps are used; other factors include water flow rate, water quality, and contact chamber size. The median energy requirement for low-pressure lamps is 64 kWh per million gallons (0.017 kWh/m^3), with low and high estimates of 57 and 70 kWh per million gallons (0.015 and 0.018 kWh/m^3), respectively (Mackey et al., 2001; PG&E, 2006). The median energy requirement for medium-pressure lamps is 150 kWh per million gallons (0.040 kWh/m^3), with low and high estimates of 100 and 160 kWh per million gallons (0.026 and 0.042 kWh/m^3), respectively (Chang et al., 2008; Mackey et al., 2001; PG&E, 2006). Variability among water systems is likely driven by feed water transmittance, dose requirements, lamp fouling, and lamp configuration and placement (Chang et al., 2008). These estimates represent the energy requirements for UV disinfection alone and do not include energy requirements for conventional water treatment, for example, coagulation, sedimentation, and filtration.

Table 4.4. Energy Requirements for Advanced Water Treatment Technologies

	Low Value (kWh/MG)	Median Value (kWh/MG)	High Value (kWh/MG)	Data Points
UV disinfection				
Low-pressure lamps	64	57	70	2
Medium-pressure lamps	150	100	160	3
Ozone disinfection	120	160	440	8

Note: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartile, respectively.

Data sources: AWWA, 2005; Chang et al., 2008; Karns, 2004; Mackey et al., 2001; PG&E, 2006.

4.3.4 Low-Pressure Membranes for Drinking Water Treatment

Since the early 1990s, low-pressure membrane systems, such as microfiltration (MF) and ultrafiltration (UF), have become increasingly common (AWWA 2005). All membranes act as physical barriers that exclude particles based on their size. Low-pressure membrane

systems are typically applied for the removal of particulate matter and microbial contaminants. MF and UF can be used as a standalone treatment, as a replacement for particle removal processes in an existing conventional treatment plant, or as a pretreatment option for nanofiltration or reverse osmosis. Limited data are available on the energy requirements for each of these systems. Here, we evaluate the energy requirements for a standalone treatment plant, whose functions typically consist of raw water screening, a primary and sometimes secondary membrane treatment train, and disinfection. Based on five data points, we estimate that the median energy requirement for MF/UF is 500 kWh per million gallons (0.13 kWh/m^3), with low and high estimates of 320 and 750 kWh per million gallons (0.085 and 0.20 kWh/m^3), respectively (AWWA, 2005; Mackey et al., 2001; Chang et al., 2008). Facilities at the high end of the range include those operating below their design capacity and those treating water at a low temperature or at a high turbidity level (Chang et al., 2008).

4.3.5 Brackish Water Desalination

Brackish water desalination is becoming increasingly common. Although a number of desalination technologies are available, most, if not all, newly proposed plants use reverse osmosis membranes. Energy requirements for reverse osmosis, however, are highly dependent on the salinity of the source water. By definition, brackish water has a salinity concentration ranging from 0.5 to 30 parts per thousand (ppt).

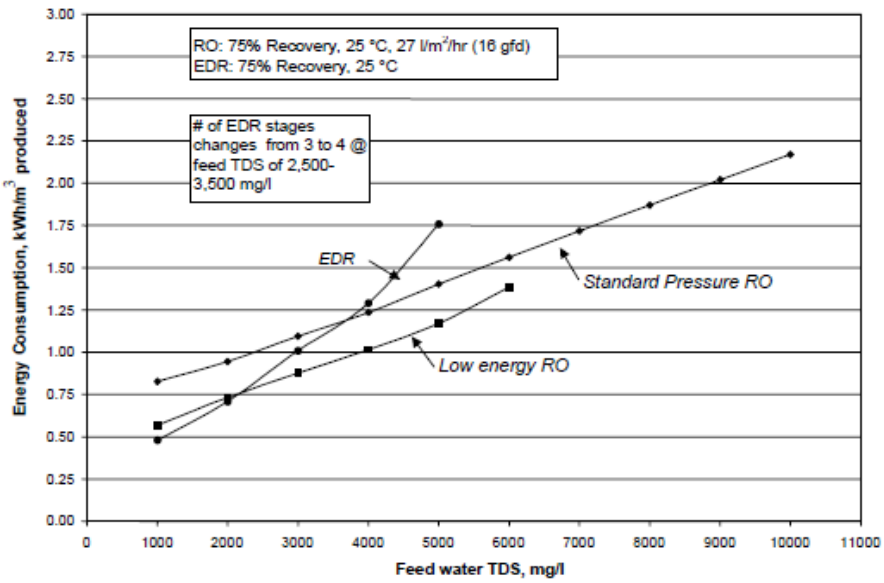

Figure 4.3. Energy intensities for brackish water desalination.

Data source: Figure 7-8 in Bureau of Reclamation, 2003.

Table 4.5. Energy Requirements for Brackish Water Desalination by Source Water Salinity

Source Water Salinity (mg/l)	Energy Intensity (kWh/MG)
1000–3000	3000–4200
3000–5000	4200–5300
5000–7000	5300–6400
7000–10,000	6400–8300

Note: Numbers reported to two significant digits.

Data source: Based on Figure 7-8 in Bureau of Reclamation, 2003.

Energy requirements for brackish water desalination are highly variable, driven in part by the fact that the salinity of brackish water varies by a factor of six. Limited data, however, are available on plants in operation and their actual energy use. The Bureau of Reclamation, in its 2003 Desalting Handbook for Planners, developed estimates of energy requirements by source water salinity (Figure 7-8 in the original document and reproduced as Figure 4.3). Given high variability and limited data, default values in WESim are based on data for standard-pressure reverse osmosis in Bureau of Reclamation (2003) and are shown in Table 4.5. Energy requirements are provided as a range, with values at the higher end of the range associated with higher salinity source water.

4.3.6 Seawater Desalination

A wide variety of desalination technologies effectively remove salts from salty water (or extract fresh water from salty water), producing a water stream with a low concentration of salt (the product stream) and another with a high concentration of the remaining salts (the brine or concentrate). Most of these technologies rely on either distillation or membranes to separate salts from the product water.

The earliest plants were based mostly on large-scale thermal evaporation or distillation of seawater, mimicking the natural hydrologic cycle. Since the 1970s, more plants have been installed that use membranes that mimic the natural biological process of osmosis, because these systems have a number of advantages over thermal systems. In particular, membrane technologies can desalinate both seawater and brackish water, can remove microorganisms and many organic contaminants, and generally have lower capital costs and require less energy than thermal systems. As a result, almost all of the newly proposed plants use membrane technologies, and specifically reverse osmosis.

Energy requirements for seawater desalination using reverse osmosis have declined dramatically over the past 30 years. Given these improvements, we evaluate energy requirements at 15 plants contracted for in 2005 and later (Table 4.6). The median energy requirement for these plants is 15,000 kWh/MG (4.0 kWh/m^3), with low and high estimates of 14,000 and 16,000 kWh/MG (3.7 and 4.2 kWh/m^3), respectively. Variability is driven by a variety of factors, including source water salinity, temperature, product water quality, and the presence of energy recovery devices.

Table 4.6. Energy Requirements for Seawater Desalination Using Reverse Osmosis

Plant	Energy Requirements (kWh/MG)	Facility Capacity (m^3/day)	Date Contracted
Kwinana, Perth, Australia	13,626	140,000	2005
China	15,519	34,560	2005
Egypt	15,140	1,000	2005
Raleigh IWSPP, Saudi Arabia	18,168	227,300	2005
Rambla Morales, Spain	12,491	60,000	2005
Valdelentisco, Spain	16,654	140,000	2005
Khor Fakhan Power Plant, UAE	15,140	22,700	2005
Aruba	15,140	8,000	2006
Gold Coast, Australia	13,626	125,000	2006
Israel (Hadera)	17,033	272,765	2006
Bonaire, Dutch Antilles	15,140	8,000	2006
Alicante II, Spain	14,005	65,000	2006
Fujairah 1, UAE	18,168	170,000	2006
Caofeidian Desalination Plant, China	15,140	50,000	2009
Ashkelon Expansion, Israel	14,383	41,000	2009

Source: GWI, 2010.

4.3.7 Recycled Water Treatment

For water reuse, treated wastewater represents the water "source." Thus, the treatment energy requirement for reuse is the additional energy required beyond the current wastewater treatment requirements. If wastewater is treated to primary or secondary standards before discharge, then additional treatment is required to bring it to reuse standards, and the energy required for that additional treatment should be attributed to the reused water. Thus, one of the main drivers of energy intensity is the level to which wastewater must be treated prior to discharge into the environment. If wastewater is already treated to tertiary standards before discharge and no additional treatment is required to bring it to the appropriate standard for reuse, then the energy intensity of treatment for recycled water may be zero. In some cases, treatment requirements for reuse may even be less than those for wastewater discharge, suggesting possible net energy savings with reuse. For example, nutrient removal, an energy-intensive process, might be required for wastewater discharge but not for reuse on landscapes in some areas.

Another energy driver is the level of treatment required to meet end-use standards and the treatment processes and technologies employed to achieve those standards. The technologies and processes used to recycle water depend, in part, on the quality of the water required by the end user. The EPA recommends secondary treatment plus filtration and disinfection for all urban reuse, including landscape irrigation, vehicle washing, and toilet flushing; only secondary treatment and disinfection are recommended for construction and industrial uses (EPA, 2004). The EPA provides suggested treatment levels for a wide variety of uses in its publication *Guidelines for Water Reuse*. Treatment requirements for indirect potable reuse are considerably more stringent than those for nonpotable reuse.

Table 4.7. Energy Intensity of Recycled Water Treatment

Technologies Used	Energy Use (kWh/MG)	End Use	Data Source
Conventional Tertiary Treatment			
Anthracite coal bed filtration, demineralization, chlorination	982	Irrigation, industrial use	CSA 2008
Flocculation, direct filtration, UV/advanced oxidation	1500	Irrigation, industrial use	WRF 2011
Clarification, media filtration, chlorination	1619	Irrigation, industrial and commercial use	GEI 2010a
Anthracite coal bed filtration, UV	1703	Irrigation, industrial use	CSA 2008
Rapid mix, flocculation, media filtration, and UV	1800	Irrigation	WRF 2011
Membrane Treatment			
Coagulation, flocculation, clarification, UF, RO, UV/advanced oxidation	3220	Agriculture, industrial use	WRF 2011
MF, RO, UV/advanced oxidation	3680	Groundwater recharge	Patel 2011
MF, RO, UV/advanced oxidation	3926	Seawater intrusion barrier	WRF 2011
UF, RO, UV	4050	Industrial use	WRF 2011
MF, RO	4674	Industrial use	WRF 2011
MF, RO	8300	High-quality industrial use	WRF 2011

Numerous treatment technology alternatives can often be used to achieve the same treatment goal—for example, chlorine, chloramines, UV, and ozone can all be used for disinfection. Deciding which of these technologies to implement should be done on a case-by-case basis, and can depend on a wide variety of factors including cost, reliability, and ease of operation. Additionally, environmental conditions, influent water quality, and regulations can all impact the types of treatment technologies selected (EPA, 2004).

Detailed surveys have not yet been conducted on the energy requirements for water reuse treatment, and thus our estimates are based on 11 case studies found throughout the literature and through personal communication (Table 4.7). The case studies demonstrate a wide range of energy requirements for water reuse, from around 980 kWh to more than 8300 kWh per million gallons (0.26 to 2.2 kWh/m^3). For all case studies, the "source water" was wastewater that had previously received secondary treatment. Typically, these case studies report a single energy estimate for an entire facility; thus, it is difficult to determine the energy requirements for each element of the treatment train.

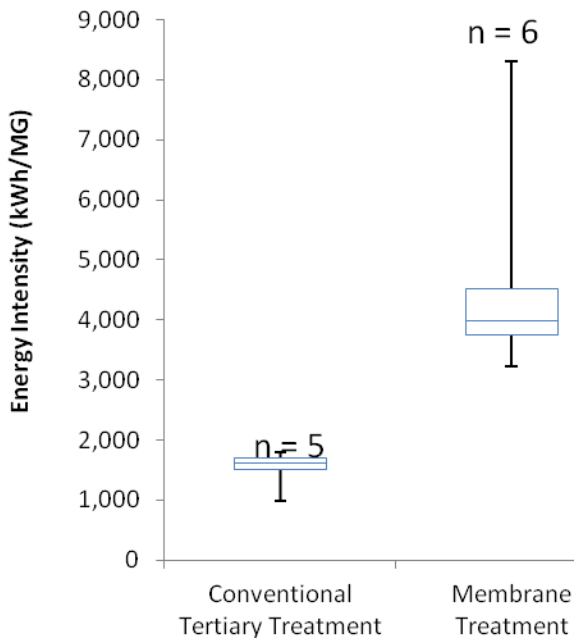

Figure 4.4. Energy intensity of recycled water treatment.

For the case studies reviewed, treatment processes could be divided into two categories: conventional tertiary treatment and membrane treatment. Conventional tertiary treatment trains consist of filtration and disinfection. Membrane treatment consists of either ultrafiltration or microfiltration, followed by reverse osmosis, and commonly UV disinfection. Based on five data points, we estimate that energy requirements for conventional tertiary treatment have a median value of 1600 kWh per million gallons (0.42 kWh/m^3), and low and high values of 1500 and 1700 kWh per million gallons (0.40 to 0.45 kWh/m^3) (CSA, 2008; WRF, 2011; GEI, 2010b). This represents the energy requirements for taking wastewater that was previously treated to secondary standards to a standard appropriate for reuse. Energy requirements for membrane treatment have a median value of 4000 kWh per million gallons (1.1 kWh/m^3), and low and high values of 3700 and 4500 kWh per million gallons (0.98 to 1.2 kWh/m^3) (WRF, 2011; Patel, 2011) (Table 4.7; Figure 4.4). Data provided in Table 4.7 provide an indication of the variability among the case studies.

As noted, there are limited recycled water case studies available. As a result, a user may not find the treatment train that he or she is considering. The format of WESim is such that these defaults are not hardwired into the model. Rather, the user can add whatever value he or she thinks is appropriate.

4.4 Water Distribution

Water distribution is the transport of treated water from a treatment facility to customers. As with conveyance, the energy intensity of distribution depends largely on the distance and elevation through which water is pumped, as well as the energy efficiency of pumps. In the following section, we describe distribution energy requirements for potable and recycled water.

Table 4.8. Energy Intensity for Water Distribution

	Energy Intensity (kWh/MG)
Low value (kWh/MG)	360
Median value (kWh/MG)	540
High value (kWh/MG)	860
Data points	41

Note: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartile, respectively.

Data sources: Burton, 1996; CEC, 2005; CSA, 2008; ECONorthwest, 2011; GEI, 2010b; Maas, 2009; PG&E, 2007; Sauer and Kimber, 2002; SCVWD, 2007; Tellinghuisen, 2009; Wilkinson, 2000; Wolff et al., 2004.

4.4.1. Potable Water Distribution

Based on 41 data points, the median energy requirement for water distribution is 540 kWh per million gallons (0.14 kWh/m^3), with low and high values of 360 and 860 kWh per million gallons (0.095 and 0.23 kWh/m^3) (PG&E, 2007; Sauer and Kimber, 2002; GEI, 2010b; Tellinghuisen, 2009; ECONorthwest, 2011; Burton, 1996; Maas, 2009; Wolff et al., 2004; Wilkinson, 2000; CSA, 2008; SCVWD, 2007; CEC, 2005) (Table 4.8; Figure 4.5). Most studies reviewed do not contain sufficient data to classify the water system topography. Some contain qualitative descriptions, e.g., moderate or hilly, although definitions for these general categories were not provided. Furthermore, a single facility might have both treatment processes and distribution pumps but only a single meter.

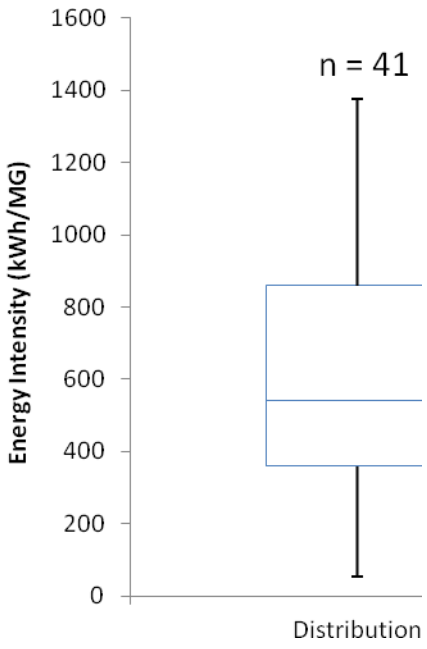

Figure 4.5. Energy intensity for water distribution.

Given a lack of information to better characterize these distribution systems, we supplement these estimates with data from the 2007 AwwaRF study. A regression analysis on data from 86 utilities across the United States revealed that the flow, the distribution pump horsepower, the range in elevation, and the presence or absence of lagoon dewatering, pressure filtration, or residual gravity thickening explain 78% of the distribution energy use variation (AwwaRF 2007, p. 52). The model form is

$$EI = \exp(7.4356 + 0.5047 \ln(calc_flow) + 0.5579 \ln(distrib_hp) + 0.1441 \ln(calc_elev_change + 1) + 0.6928\, res_lagoon - 1.7926\, process_filtr_press + 0.7122\, res_gravity) \quad (4.4)$$

where

EI	=	Source energy intensity for potable water distribution, in thousand Btu (kBtu) per year
calc_flow	=	Average daily total flow, in thousand gallons per day (kgd)
distrib_hp	=	Distribution system pump horsepower, in horsepower (hp)
calc_elev_change	=	Distribution system elevation change, in feet (ft)
res_lagoon	=	Presence of lagoon dewatering thickening (0 or 1)
process_filtr_press	=	Presence of pressure filtration (0 or 1)
res_gravity	=	Presence of residual gravity thickening (0 or 1).

As noted in the AwwaRF study, the inclusion of treatment-related parameters suggests that differentiating between energy use for treatment and distribution is difficult.

WESim integrates this model into the default calculator, allowing the user to enter information on the required parameters. We recognize, however, that not all users will have access to this information, especially when conceptualizing future distribution systems. We therefore provide both the AwwaRF model and the values shown in Table 4.8. We note that the AwwaRF study does not contain data on recycled water distribution, and thus this equation is not appropriate for these systems. Recycled water is discussed separately next.

4.4.2. Recycled Water Distribution

Distribution energy requirements for recycled water are variable, depending on the location of the end user. In some cases, energy requirements for distributing recycled water may be higher than for potable water because wastewater treatment facilities are typically located at the lowest point of the service area. For nonpotable reuse, recycled water is distributed to customers through a separate distribution system. Through an extensive literature review, we identified 13 case studies that provided energy-intensity estimates for recycled water distribution. Based on these studies, we estimate that the energy intensity of recycled water distribution has a median value of 1400 kWh per million gallons (0.37 kWh/m^3), and low and high values of 1000 and 3000 kWh per million gallons (0.26 and 0.79 kWh/m^3), respectively (GEI, 2010b; CSA, 2008; PG&E, 2007; SCVWD, 2007) (Table 4.9). Detailed surveys are needed to develop more robust estimates of the energy intensity of recycled water distribution and the primary factors affecting this energy use.

Table 4.9. Energy Intensity of Recycled Water Distribution

	Energy Intensity (kWh/MG)
Low value (kWh/MG)	1000
Median value (kWh/MG)	1400
High value (kWh/MG)	3000
Data points	13

Note: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartiles, respectively.

Data sources: CSA, 2008; GEI, 2010b; PG&E, 2007; SCVWD, 2007.

Indirect potable reuse, whereby recycled water is treated to potable standards and then used to recharge groundwater or surface reservoirs, is becoming increasingly common. For indirect potable reuse, distribution refers to the transport of water from the recycled water facility to the surface or groundwater reservoir. In the case of direct injection, it would include the energy required to pump the water underground. No data are currently available on energy requirements for distributing recycled water for indirect potable reuse.

4.5 Wastewater Collection

Wastewater collection refers to the collection and transport of wastewater from the customer's home to a wastewater treatment facility. In some cases, wastewater collection is done by gravity, although pumping is required in some areas. Based on the available studies, energy requirements for wastewater collection have a median value of 280 kWh per million gallons (0.074 kWh/m^3), and low and high values of 140 and 440 kWh per million gallons (0.037 and 0.12 kWh/m^3) (PG&E, 2007; CSA, 2008; Sauer and Kimber, 2002; ECONorthwest, 2011; Navigant, 2006; CEC, 2005; Maas, 2009) (Table 4.10; Figure 4.6). Variability in the energy requirements for wastewater collection is dependent upon local geography and pump efficiency, with flatter topography associated with the lower end of the range.

Table 4.10. Energy Intensity of Wastewater Collection

	Energy Intensity (kWh/MG)
Low value (kWh/MG)	140
Median value (kWh/MG)	280
High value (kWh/MG)	440
Data points	29

Note: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartiles, respectively.

Data sources: CEC, 2005; CSA 2008; ECONorthwest, 2011; Maas, 2009; Navigant, 2006; PG&E, 2007; Sauer and Kimber, 2002.

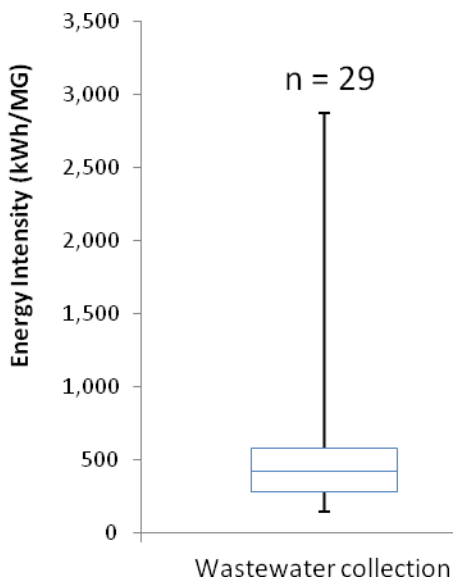

Figure 4.6. Energy intensity of wastewater collection.

Like the water distribution data, the wastewater collection data show a tremendous amount of variability and insufficient information to better characterize the primary drivers. The AwwaRF 2007 study collected wastewater collection data from 171 utilities across the United States and performed a regression analysis. The model estimates energy requirements for wastewater collection based on the average flow, number of pumps, and total pumping horsepower. These parameters explain 67% of the collection system energy-use variability, and the model residuals are randomly distributed (AwwaRF 2007, p. 99). The model form is

$$EI = \exp(10.0264 + 0.3523 \ln(inf_average) + 0.6409 \ln(pump_hp) + 0.2292 \ln(pump_num)) \quad (4.5)$$

where

EI	=	Source energy intensity, in thousand Btu (kBtu) per year
inf_average	=	Average influent flow, in million gallons per day (mgd)
pump_hp	=	Collection system pumping power, in horsepower (hp)
pump_num	=	Number of pumps.

The study also developed a five-parameter model, which included information about various wastewater treatment processes. This expanded model, however, provides only a slight improvement in the model R^2 correlation statistic. Thus, we determine that the simpler three-parameter model is adequate for inclusion in WESim. We recognize that not all users will have this information, especially for future systems, and thus provide the three-parameter model as well as the default values shown in Table 4.10.

4.6 Wastewater Treatment

Wastewater treatment refers to the treatment of wastewater prior to reuse or disposal into the environment. The energy requirements for wastewater treatment depend on the level of treatment and, because wastewater must be pumped through the treatment facility, pump efficiency. There is significant variation in the energy requirements for different levels of wastewater treatment. Unless otherwise indicated, all energy-intensity values reported include all preceding treatment stages; that is, secondary treatment energy includes both primary and secondary treatment.

Wastewater treatment is classified as primary, secondary, or tertiary. With primary treatment, physical barriers remove solids, oil, and grease from the wastewater. Secondary treatment is designed to promote the degradation of the biological content of wastewater using biological processes, which may include aerobic stabilization ponds, trickling filters, activated sludge processes, and lagoons. Activated sludge treatment, which relies on the addition of oxygen and bacteria to wastewater to reduce the organic content in the wastewater, is one of the most common treatment methods. If receiving waters require that wastewater effluent contain particularly low nutrient content, or if the wastewater is going to be reused, it also undergoes tertiary treatment to reduce nitrogen, phosphorus, and other contaminant concentrations. Tertiary treatment is becoming more common as water discharge regulations become increasingly stringent.

A significant body of work has focused on quantifying the energy use of wastewater treatment facilities and approaches to reducing that use. The most comprehensive analysis, conducted by AwwaRF (2007), included energy use and operational characteristics of 266 wastewater treatment plants across the United States. A regression analysis revealed that energy use relates to the average influent flow, the influent biological oxygen demand (BOD), the effluent BOD, the ratio of average influent flow to design influent flow, and the use of trickle filtration and nutrient removal. These parameters explained 82% of the treatment plant energy variability, and the model residuals were randomly distributed (AwwaRF 2007, p. 80). The model form is

$$\begin{aligned} EI = exp(&15.8741 + 0.8944 \ln(inf_average) + 0.4510 \ln(inf_bod) \\ &- 0.1943 \ln(eff_bod) - 0.4280 \ln(inf_lf) - 0.3256\, process_tf \\ &+ 0.1774\, treat_nr) \end{aligned} \tag{4.6}$$

Where

EI	=	Source energy intensity, in thousand Btu (kBtu) per year
inf_average	=	Average influent flow, in million gallons per day (mgd)
inf_bod	=	Influent BOD, in milligrams per liter (mg/L)
eff_bod	=	Effluent BOD, in milligrams per liter (mg/L)
inf_lf	=	$\text{Influent load factor} = \left(\frac{\text{Average Flow}}{\text{Design Flow}}\right) \times 100$
process_tf	=	Presence of trickle filtration (0 or 1)
treat_nr	=	Presence of nutrient removal (0 or 1).

WESim integrates this model into the default calculator, allowing the user to enter information on the required parameters. We recognize that not all users will have this information. The 2007 AwwaRF study collected data on the treatment energy requirements, facility size, and the level of treatment. Based on these data, we produce estimates for wastewater treatment by facility size and level of treatment (Tables 4.11–4.13). As expected, treatment energy requirements generally increase as the level of treatment increases and decline as the facility size increases. Variability within a given size class is largely driven by influent and effluent water quality and the type of processes employed. Facilities with high influent BOD levels, low effluent BOD levels, and nutrient removal processes are at the high end of the range, whereas those with lower influent BOD levels, higher effluent BOD levels, and trickle filtration processes are at the lower end of the range.

Table 4.11. Energy Intensity for Secondary Treatment by Facility Size

	1–5 MGD	5–20 MGD	20–50 MGD	50+ MGD
Low value (kWh/MG)	1500	1400	1200	960
Median value (kWh/MG)	2300	2000	1600	1400
High value (kWh/MG)	3100	2500	2000	2100
Data points	78	67	25	27

Note: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartiles, respectively.

Data source: Based on data in AwwaRF, 2007.

Table 4.12. Energy Intensity for Advanced Treatment I by Facility Size

	1–5 MGD	5–20 MGD	20–50 MGD	50+ MGD
Low value (kWh/MG)	1900	2000	1200	1800
Median value (kWh/MG)	2200	2500	2000	2000
High value (kWh/MG)	2900	2900	2100	2100
Data points	11	27	5	5

Note: Advanced treatment I refers to EPA NPDES permit levels for BOD_5 (30-day average) between 10 and 20 mg/l. Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartiles, respectively.

Data source: Based on data in AwwaRF, 2007.

Table 4.13. Energy Intensity for Advanced Treatment II by Facility Size

	1–5 MGD	5–20 MGD	20–50 MGD	50+ MGD
Low value (kWh/MG)	2200	2300	1800	1700
Median value (kWh/MG)	3300	3000	2400	1800
High value (kWh/MG)	4800	3300	4300	2300
Data points	10	8	6	6

Note: Advanced treatment II refers to EPA NPDES permit levels for BOD_5 (30-day average) less than 10 mg/l. Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartiles, respectively.

Data source: Based on data in AwwaRF, 2007.

Table 4.14. Energy Intensity of Wastewater Discharge

	Energy Intensity (kWh/MG)
Low value (kWh/MG)	0
Median value (kWh/MG)	0
High value (kWh/MG)	0
Data points	9

Note: Numbers reported to two significant digits. The low and high estimates correspond to the first and third quartile, respectively.

Data sources: ECONorthwest, 2011; EPRI, 2002; PG&E, 2007.

4.7 Wastewater Discharge

Wastewater discharge refers to the discharge of treated wastewater into the environment. Wastewater discharge can be done by gravity or may require pumping. Although typically small, the energy requirements for wastewater discharge depend upon local geography and pump efficiency. Based on nine data points, energy requirements for wastewater discharge have a median value of 0 kWh per million gallons (Table 4.14). For those plants discharging into the ocean, rising seas may increase future discharge-pumping requirements; the user is encouraged to explore this as one potential future scenario, if appropriate.

4.8 Customer End Use

Customer end use of water refers to the multitude of ways that we use water in residential, commercial, industrial, institutional, and agricultural settings, which include personal hygiene, dish and clothes washing, landscape and crop irrigation, process water, and equipment cooling. Energy use associated with customer water end use is typically associated with heating, cooling, water treatment (e.g., filtering and softening), circulation, and supplemental pressurization in high rises.

WESim is flexible enough to allow the user to enter any end use for which he or she has adequate energy-intensity data. The user can simply create a “facility” (in this case the “facility” refers to a particular end use, such as showers), enter the volume of water associated with that facility/end use, and enter the energy intensity of that water. WESim will also provide a range of defaults to allow the user to estimate the end use energy associated with water heating, which constitutes the vast majority of end use energy. This estimation is done based on either the percentage of hot water or the end use temperature. For both methods, the user must enter the water inlet temperature, for example, the average temperature at which water enters the residence or business. The model assumes 55°F/13°C, although users can customize this information based on average inlet temperatures for 277 different locations in the United States from Mills (2008). The user must also enter the water heat efficiency. The model assumes 90% efficiency for electric water heaters, 55% efficiency for natural gas water heaters, and 59% efficiency for fuel oil-powered water heaters, although users are allowed to select appropriate values.

- For the percentage hot water method, the user must specify the hot water heater temperature (130°F/54°C is common) and the percentage of the water use that is hot water. For example, clothes washers (with the warm setting) use 40% hot water and 60% cold water.

- For the end use temperature method, the user must specify the water temperature associated with a particular end use. For example, residential dishwashers typically use water heated to 139°F/59°C (dishwashers typically have a booster heater to heat water from the water heater temperature to the desired end use temperature). The model includes the defaults shown in Table 4.15 for end use temperature.

WESim does not include any assumptions about the volume of water that is delivered to a particular end use. Doing otherwise would lock the user into a particular configuration of end uses that may change as new homes and businesses are constructed or as conservation and efficiency are pursued. Instead, the user is allowed to enter the volume of water dedicated to a particular end use within his or her service area. Most residences have both indoor and outdoor water use, which the share of each dependent on a variety of local conditions. Users are encouraged to estimate the percentages of indoor and outdoor use based on local billing data or regional estimates. Detailed end-use information is typically not available, although Table 4.16 provides a rough breakdown of indoor and outdoor use by end use from a national survey conducted in the late 1990s. Users can enter these data if they do not have a breakdown specific to their service area. Once the user has determined residential indoor and outdoor use, he or she can use these percentages to estimate water use by end use. The user can then develop a "facility" for each end use. If conservation and efficiency efforts target clothes washers and the user is able to estimate savings from these efforts, then the user can develop an alternative scenario that reduces clothes washer water use by the expected water savings.

Table 4.15. End Use Temperatures for Various Water Uses

End Use	End Use Temperature		Data Source
	°C	°F	
Sink filling	41	105	Koomey et al., 1994
Faucet flow	27	80	Koomey et al., 1994
Bath	38	100	Koomey et al., 1994
Shower	41	105	Koomey et al., 1994
Commercial/residential clothes washer	26	78	Koomey et al., 1994
Dishwasher	59	139	Koomey et al., 1994
Commercial spray valves	49	120	CEE, no date
Commercial dishwasher	82	180	Food Service Technology Center, 2002

Table 4.16. Residential End Uses of Water

Use Category	End Use	% of Sector Total
Indoor residential	Toilets	27
	Showers/baths	19
	Faucets	16
	Dishwasher	1
	Clothes washers	22
	Leaks	14
	Other domestic	2
Outdoor residential	Landscaping	100

Note: Some categories do not add up to 100% because of rounding.
Data source: Mayer et al., 1999.

A similar methodology can be applied to commercial and industrial uses of water. Detailed surveys, however, are generally lacking for commercial, industrial, and institutional water use by end use. In some cases, agencies may have collected these data. If not, the user should consider using the values shown in Tables 4.17 and 4.18, which are described in Appendices E and F of Gleick et al. (2003).

Table 4.17. Commercial End Uses of Water

Sector	End Use	Water Use (%)	Sector	End Use	Water Use (%)
Office buildings	Toilets	12.20	Grocery	Restrooms	17
	Urinals	3.20		Cooling	49
	Faucets	0.70		Other	22
	Landscaping	28.80		Kitchen	9
	Cooling	32.40		Landscaping	3
	Kitchen	4.50	Misc. retail	Restrooms	26
	Other	17.60		Cooling	21
Hotels	Showers	27.10		Landscaping	38
	Faucets	0.50		Kitchen	4
	Toilets	9.20		Other	11
	Landscaping	7.70	Elementary and middle schools	Landscaping	63.10
	Pool	0.40		Toilets	16.40
	Cooling	6.20		Urinal	4.20
	Kitchen	13.10		Faucet	0.80
	Laundry	15.40		Kitchen	10.40
	Ice-makers	0.80		Other	5.20
	Other	19.20			
High schools	Landscaping	77.40	Hospitals	Restrooms	25.0
	Toilets	8.80		Landscaping	16.0
	Urinal	2.20		Cooling	27.0
	Faucet	0.40		Kitchen	8.0
	Kitchen	5.60		Laundry	2.0
	Other	5.60		X-ray	4.8
Other schools	Landscaping	43.90		Steam sterilizers	5.1
	Toilets	19.70		Laboratories	2.2
	Urinal	3.80		Boilers	2.2
	Faucet	0.60		Vacuum pumps	8.8
	Kitchen	25.50	Restaurants	Pre-rinse spray nozzles	6.1
	Other	6.40		Pot and pan sink	12.1
Laundries	Restroom	5		Garbage disposal	5.4
	Laundry	85		Dishwasher	17.3
	Cooling	5		Restrooms	27.2
	Boiler	5		Prep sink	1.2
				Water used in food	5.0
				Ice-maker	15.1
				General sanitation	6.5
				Other	4.0

Note: Some categories may not add up to 100% because of rounding.

Data source: Appendix E in Gleick et al., 2003.

Table 4.18. Industrial End Uses of Water

Sector	End Use	Water Use (%)
Meat processing	Restroom	8.0
	Cooling	33.0
	Landscaping	1.0
	Process	58.0
Dairy	Restroom	3.0
	Cooling	71.0
	Landscaping	3.0
	Carton washing	1.6
	Cold storage	0.7
	Utilities	8.1
	Sanitation equipment, filling room, receiving	11.5
	Consumption	1.2
Preserved fruits and vegetables	Cooling	22.0
	Landscaping	3.0
	Produce and equipment cleaning	54.8
	Utilities/boilers	18.3
	Other	2.0
Beverages	Restroom	3.0
	Cooling	5.0
	Process	45.0
	Consumption	46.0
	Other	1.0
Textile industry	Cooling	5.0
	Other	5.0
	Preparation	13.5
	Dyeing	46.8
	Printing	5.0
	Washing	24.3
Fabricated metals	Process	67.0
	Cooling	15.0
	Kitchen	1.0
	Other	17.0
High-tech industry	Restrooms	5.0
	Rinsing	56.0
	Scrubbers	7.0
	Ultrapurified water production	7.0
	Cooling	20.0
	Other	5.0
Paper and pulp industry	Boiler	4.0
	Cooling	4.0
	Process	88.0
	Other	4.0
Petroleum refining	Cooling	57.0
	Process	6.0
	Boiler	34.0
	Other	3.0

Note: Some categories may not add up to 100% because of rounding.

Data source: Appendix F in Gleick et al., 2003.

Chapter 5

Case Studies

WESim has a variety of applications. For example, it can be used to evaluate the energy and greenhouse gas implications of population growth, the impact of climate change, development of alternative water sources, and water treatment improvements required by emerging contaminants and stricter water-quality guidelines. It can also be used to evaluate how the installation of renewable-energy systems and energy efficiency improvements can reduce greenhouse gas operations.

In this report, we provide case studies that demonstrate two applications of WESim. In the first example, we use WESim to evaluate how population and economic growth, implementation of water conservation and efficiency measures, and pursuit of recycled water would impact the Santa Clara Valley Water District's energy use and greenhouse gas emissions in 2009 and in 2020. For this application, we combined the current and projected water demand data with energy-intensity estimates, in kWh per million gallons, developed by the district in an earlier analysis.

In the second example, we use WESim to explore different system configurations for Denver Water. Denver Water operates three treatment plants that are situated at different elevations. Energy requirements to move water away from the treatment plants vary dramatically. For this application, we use water flow and energy data (electricity, natural gas, and diesel) for each facility for 2008 and evaluate the energy and greenhouse gas savings associated with increasing flows at the lower-elevation treatment plants. In contrast to the Santa Clara Valley Water District example, total water flow and water sources remained constant. Additional detail on each of the case studies follows.

5.1 Santa Clara Valley Water District

5.1.1 Introduction

The Santa Clara Valley Water District (SCVWD) is a wholesale water-service provider that sells treated water to 13 water retailers, including five private companies. These retailers, in turn, provide water to approximately two million people—1.8 million residents and 200,000 commuters—in 15 cities and unincorporated areas in Santa Clara County, California (Figure 5.1). The SCVWD is also responsible for flood protection within the county.

The SCVWD relies on a diverse portfolio of water resources, including local surface and groundwater; water imported from the Central Valley Project, the State Water Project, and the Hetch Hetchy system; and recycled water. The SCVWD owns and operates 10 water reservoirs and manages groundwater throughout the county. It also owns and operates three water treatment facilities, two of which use ozone, rather than chlorine, as the primary disinfectant. After treatment, the SCVWD distributes treated water to its 13 water retailers.

Figure 5.1. Map showing location of the Santa Clara Valley Water District service area.
Source: SCVWD, 2011a.

The SCVWD has been a leader in evaluating the energy requirements and greenhouse gas emissions from its water management decisions. In 2007, the District released its report *From Watts to Water: Climate Change Response through Saving Water, Saving Energy, and Reducing Air Pollution*, which quantified the energy savings and air emissions reductions associated with its water conservation and water recycling efforts. An updated analysis was released in 2011. The District estimates that water conservation and efficiency programs implemented since 1992 have cumulatively saved 429,000 acre-feet of water. Water recycling programs have cumulatively saved 118,000 acre-feet of water. These water savings have resulted in a savings of 2.67 billion kilowatt-hours (kWh) of electricity, which represents a financial savings of approximately $347 million, and have eliminated the emission of 625 million kg of carbon dioxide**,** as well as a range of other pollutants, including reactive organic gases, nitrogen oxides**,** sulfur oxides, and particulate matter smaller than 10 μm, or PM10. The installation of solar panel arrays has produced an additional 2.1 million kWh of electricity and reduced emissions of carbon dioxide by 1.5 million kg (SCVWD, 2011b).

The SCVWD is considering a range of water supply options and conservation strategies to meet future water demands. The District views recycling and water conservation and efficiency as a means of mitigating climate change, and in 2008, the Board passed a resolution to minimize greenhouse gas emissions and "achieve carbon-neutrality as soon as is practicable." The District is pursuing a range of emissions reduction strategies, including water conservation and efficiency, increased use of recycled water, development and use of alternative energy sources, and improved energy efficiency measures.

5.1.2 Model Inputs

The SCVWD is interested in using WESim to evaluate how population and economic growth, implementation of water conservation and efficiency measures, and pursuit of recycled water would impact the District's energy use and greenhouse gas emissions. For this analysis, we construct the Baseline Scenario using water flow data for each water and wastewater system component for 2009, as reported in the most recent Urban Water Management Plan

(SCVWD, 2011a). We then develop two scenarios for 2020. The first 2020 scenario is based on projected water demand for that year and the portfolio of supplies expected to meet that demand, as reported in the 2010 Urban Water Management Plan. This scenario includes nearly 7300 million gallons of recycled water and is referred to as the "2020 with Recycled Water" scenario. We also develop a 2020 scenario without recycled water but with greater reliance on local groundwater and imported surface water, termed the "2020 without Recycled Water" scenario. We then combine the current and projected water demand data with energy-intensity estimates developed by the SCVWD in an earlier analysis. This assumes that energy-intensity estimates remain constant over time, which is unlikely but is necessary based on limited information available at this time. The energy-intensity estimates are summarized in Table 5.1. Rather than specific data being input for each facility, facilities are grouped according to their primary purpose. For example, all groundwater wells are input as a single facility.

Table 5.1. Energy Intensity for Water System Elements within the Santa Clara Valley Water District

		Energy Intensity (kWh/MG)
Extraction	Groundwater	1712 (2777)[a]
	Imported water	0
	Recycled water	0
Conveyance	Imported water conveyance	2200
	Groundwater conveyance	0
Treatment	Surface water treatment	267
	Groundwater treatment	0
	Recycled water treatment (tertiary)	0
	Advanced recycled water treatment	1600
Distribution	Groundwater distribution	273
	Imported water distribution	1197
	Recycled water distribution	1135
Wastewater collection		0
Wastewater treatment		2366[b]
Wastewater discharge		0

Notes: [a] Energy required for groundwater pumping (1712 kWh per million gallons) refers to pumping requirements, whereas the number in parentheses (2777 kWh per million gallons) includes energy embedded in the imported water that is used to recharge groundwater.
[b] Energy requirements for wastewater treatment include collection, treatment, and discharge.

Source: SCVWD, 2011b.

Table 5.2. Water Supply Portfolio for the Santa Clara Valley Water District in 2009 and in 2020 with and without Recycled Water

	2009 Flows (million gallons)	2020 Flows with Recycled Water (million gallons)	2020 Flows without Recycled Water (million gallons)
Groundwater	50,572	47,255	51,427
Local surface water[a]	0	0	0
Imported water	69,080	76,836	81,008
Recycled water (tertiary)	4,717	4,864	0
Recycled water (advanced)	0	2,396	0

Note s: [a] Local surface water is used largely for environmental purposes, and although it represents part of the district's portfolio, it is not included here.

Sources: SCVWD, 2011a and Larabee, personal communication.

Table 5.3. Greenhouse Gas Emission Factors for Electricity Sources Powering the Santa Clara Valley Water District Facilities

	Emission Factors (kg/kWh)		
Electricity Source	**Carbon Dioxide (CO_2)**	**Methane (CH_4)**	**Nitrous Oxide (N_2O)**
PG&E	0.288	1.32×10^{-5}	4.54×10^{-6}
PWRPA	0.181	3.4×10^{-6}	3.4×10^{-7}

Sources: CO_2 factors for PG&E from Table G.6 in CARB, 2010; CH_4 and N_2O factors for PG&E are based on the average California grid in 2007 from Table G.7 in CARB, 2010. Emissions factors for PWRPA were developed based on the assumption that 33% of electricity is from natural gas and the remainder from hydropower and other renewables.

Facilities in the SCVWD service area are largely powered by electricity provided by Pacific Gas and Electric Company (PG&E) and the Public Water Resources Pooling Authority (PWRPA). Verified electricity CO_2 emission factors for PG&E in 2007 are based on data in CARB (2010) and are shown in Table 5.3. Emission factors for CH_4 and N_2O are not provided for PG&E, and therefore we rely on average data for California, as reported in CARB (2010). PWRPA relies primarily on electricity produced from renewable energy sources and some open market purchases for its customers. Although the mix varies from year to year, in an average year, 57% of the electricity generated is from large hydropower, 20% is from other renewables, and 33% is from open market purchases (mainly natural gas). Based on these percentages, we calculate the average greenhouse gas emission for electricity purchased from PWRPA (Table 5.3).

5.1.3 Model Outputs

Figures 5.2–5.4 show the energy requirements and greenhouse gas emissions in 2009 and in 2020 with and without recycled water. Note that the choice of energy provider, e.g., PG&E verses PWRPA, does not affect total energy use and thus the results in Figures 5.2 and 5.3 are presented based on the water system configuration. The energy provider, however, does affect the greenhouse gas emissions, and thus Figure 5.4 includes outputs based on the water system configuration and the energy provider.

Based on the model inputs, we estimate that the Santa Clara Valley Water District used 514,000 MWh_{-eq} of electricity to provide water and wastewater services to its customers in 2009. The water system accounts for about 80% of the energy consumed, and the wastewater sector accounts for the remaining 20%. By 2020, the district's energy use is projected to increase by 7% to 552,000 MWh_{-eq} with recycled water. Without recycled water, however, energy use would increase by 9% to 559,000 MWh_{eq}. Thus, recycled water produces an annual energy saving of 7000 $MWh_{-eq.}$

Figure 5.3 shows the energy requirements by system component in 2009 and in 2020 with and without recycled water. Without recycled water, energy requirements for all system components are larger in 2020 than in 2009. Increases in conveyance requirements to import water are especially high. With recycled water, energy requirements for extraction are lower in 2020 than in 2009 because recycled water offsets groundwater pumping, which is projected to decline in the future. Likewise, energy requirements for treatment and distribution are higher in 2020 for the recycled-water scenario compared to the no-recycled-water scenario. However, this additional energy is offset by reductions in the energy requirements for extraction and conveyance.

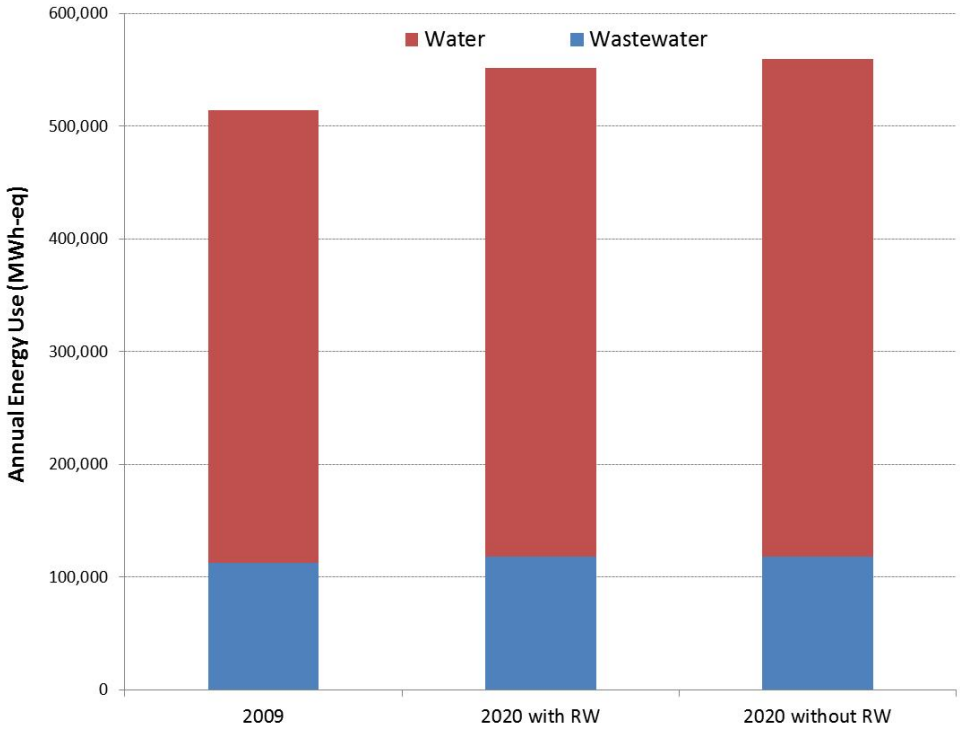

Figure 5.2. Annual energy requirements in 2009 and in 2020 with and without recycled water in the SCVWD.

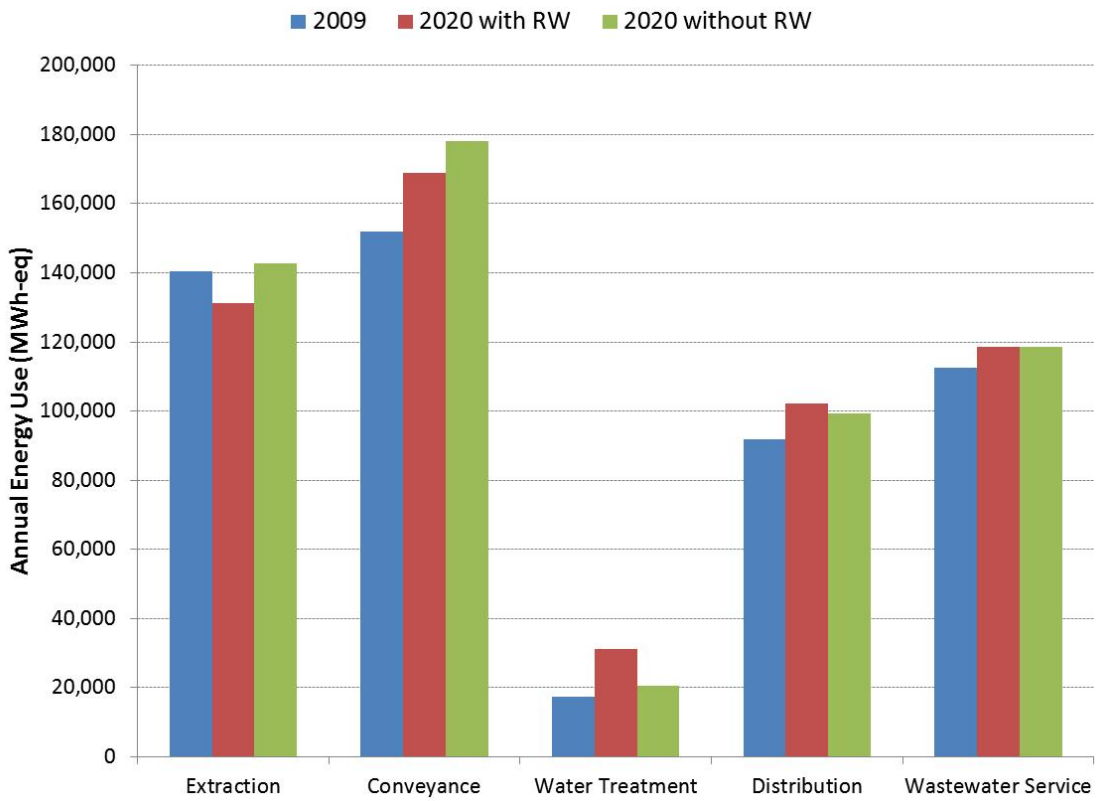

Figure 5.3. Annual energy requirements in 2009 and 2020 for each system component for the SCVWD.

Figure 5.4 shows the greenhouse gas emissions in 2009 and in 2020 with and without recycled water for each electricity provider. If electricity is provided from PG&E, then total GHG emissions in 2009 are 159,000 metric tons of $CO_{2\text{-eq}}$. Without recycled water, greenhouse gas emissions in 2020 increase by 9% relative to their 2009 levels. With recycled water, however, greenhouse gas emissions increase by about 7% relative to their 2009 levels. Thus, recycled water would reduce greenhouse gas emissions by 2280 metric tons of $CO_{2\text{-eq}}$. Shifting to PWRPA as the energy provider reduces GHG emissions by 38% in each of the water system configurations. Thus, the results indicate that switching energy providers to one more reliant on renewable energy sources and offsetting groundwater pumping and imported water with recycled water dramatically reduce greenhouse gas emissions.

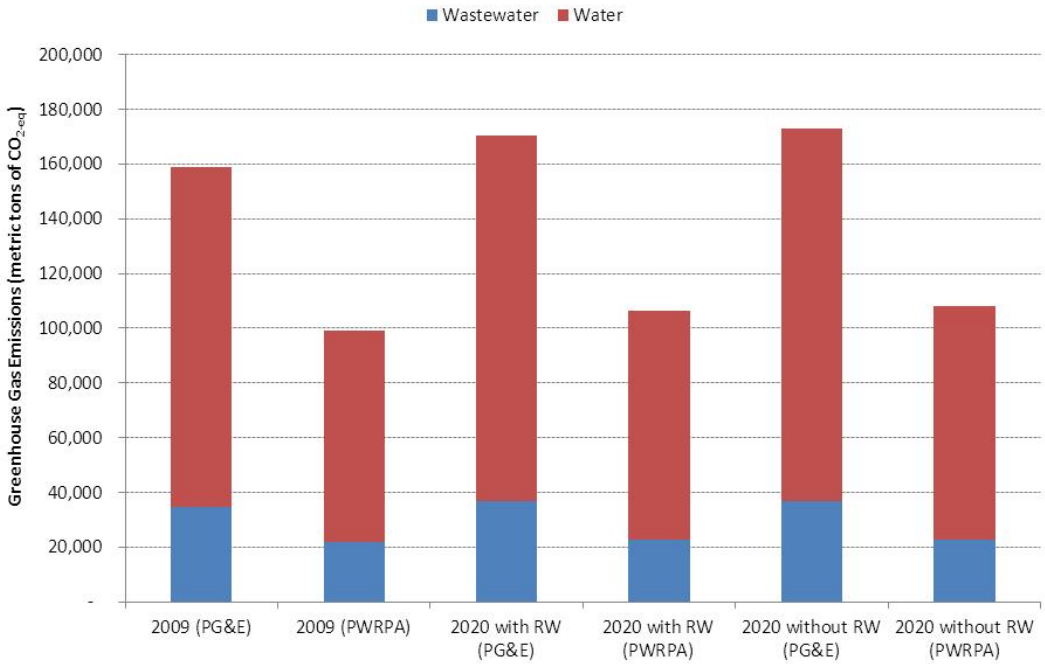

Figure 5.4. Annual greenhouse gas emissions in 2009 and 2020 with and without recycled water for the SCVWD.

5.2 Denver Water

5.2.1 Introduction

Denver Water provides water to customers within the City and County of Denver, Colorado. Denver Water also sells treated water to 78 retail agencies that serve residents in surrounding communities. In total, Denver Water and its retail water agencies serve 1.3 million people in Denver and surrounding communities.

Denver Water is largely dependent on surface water. The primary water sources include the South Platte River, Blue River, Williams Fork River, and Fraser River watersheds. Additional water sources include South Boulder Creek, Ralston Creek, and Bear Creek watersheds. In total, Denver Water owns and operates 17 water reservoirs. The water conveyance system, which moves raw water from the reservoirs to the treatment plants, covers about 4000 square miles and is largely gravity-fed. Denver Water also owns and operates three water treatment facilities. All of the treatment plants use chlorine as the primary disinfectant. These treatment plants have a total capacity of 715 million gallons per day. After treatment, Denver Water distributes treated water to its customers and water retailers through 18 pump stations and more than 3000 miles of pipeline.

Denver Water also produces and distributes recycled water. The source water for recycled water is wastewater treated to secondary standards. This wastewater is then conveyed to the Recycled Water Plant, where it undergoes additional treatment: coagulation, sedimentation, filtration, and disinfection. Once treated, the recycled water is distributed to customers

through two pump stations and more than 50 miles of pipeline. The recycled water is used for industrial purposes and for outdoor irrigation in parks, golf courses, and other public spaces.

5.2.2 Model Inputs

Denver Water is interested in using WESim to explore different system configurations. As described, Denver Water operates three treatment plants: Foothills, Marston, and Moffat. These plants are situated at different elevations in the service area, and thus pumping requirements to move water away from the treatment plant vary dramatically (note that in this case, the energy requirements for treatment include energy for pumping, as well). As a result, there are large differences in the electricity requirements of the treatment plants, as shown in Table 5.4. The Foothills Water Treatment Plans (WTP) has the lowest electricity requirements, at 101 kWh per million gallons. Electricity requirements at the Marston WTP are more than six times that amount. Under the current configuration, the Marston WTP receives larger flows than the Moffat WTP. However, Denver Water is interested in exploring the energy and greenhouse gas implications of reducing flows at the Marston WTP while augmenting those at the Moffat WTP.

For this analysis, Denver Water provides data on the total energy use, including electricity in kWh, natural gas in therms, and diesel in gallons, for each facility and the water flow through that facility. All data are for the year 2008. The data for each facility, except for the treatment plants, are entered directly into WESim. Because we are interested in exploring different flow scenarios for the treatment plants, we convert the electricity data into electricity-intensity estimates; that is, we divide the reported electricity use by the water flows (Figure 5.4). Note that although natural gas and diesel are used at the treatment plants, their use is not completely flow-dependent. Natural gas is used to run a segment of pumping, but allocating its use between pumping and nonpumping would be difficult, so we assume that the same amount of these fuels is consumed at each facility regardless of the flow through that facility. It should also be noted that not all electricity use at the plants is flow-dependent, although we do not have adequate data to adjust for this. For the treatment plants, we enter the electricity-intensity estimate into WESim. We then change the water flow through the treatment plants, as shown in Table 5.5. Note that the total flow through the treatment plants does not change; rather, we increase flow through the Moffat WTP while reducing flows through the Marston WTP by the same amount.

Table 5.4. Energy Requirements for Water Treatment Plants in the Denver Water Service Area

	2008 Flows (MG)	Electricity (kWh/MG)
Foothills Water Treatment Plant	38,400	101
Marston Water Treatment Plant	18,400	632
Moffat Water Treatment Plant	15,100	239

Note: All numbers reported to three significant digits. Energy intensity calculated based on data provided by Denver Water on energy use and water production in 2008.

Table 5.5. Water Flow Through Each Water Treatment Plant in 2008 and in Three Alternative Scenarios

	2008 (million gallons)	Alternative A (million gallons)	Alternative B (million gallons)	Alternative C (million gallons)
Foothills WTP	38,400	38,400	38,400	38,400
Marston WTP	18,400	15,100	11,700	8,390
Moffat WTP	15,100	18,400	21,800	25,200
Total Flows	72,000	72,000	72,000	72,000

Note: All numbers rounded to three significant digits.

Facilities in the Denver Water service area are powered by electricity, natural gas, and diesel fuel. WESim contains default greenhouse gas emission factors for diesel and natural gas but not electricity. The primary electricity provider for Denver Water is Xcel Energy. Utility-specific emission factors are not available for Xcel, and thus we rely on regional emission factors for 2007 for the WECC Rocky Mountain Power Area, as reported by EPA (2010).

5.2.3 Model Outputs

In 2008, we estimate that Denver Water used 74,000 MWh_{-eq} of electricity to provide water and wastewater services to its customers.[2] This is equivalent to a source energy use of 890,000 gigajoules (GJ) per year. The water system accounts for 86% of the energy consumed, and operations account for the remaining 14%.

Under the alternative scenarios, WESim shows a possible reduction in energy use and greenhouse gas emissions by more than 5% (Figure 5.5 and 5.6). Pursuing Alternative A, which shifts 3300 million gallons from the Marston WTP to the Moffat WTP, reduces energy use by 1290 MWh_{-eq} and greenhouse gas emissions by 1190 metric tons of CO_{2-eq}, or about 2%. Pursuing Alternative C and shifting 10,100 million gallons from the Marston WTP to the Moffat WTP reduces energy use by 3935 MWh_{-eq} and greenhouse gas emissions by 3641 metric tons of CO_{2-eq}, or about 5%.

Changes in system operations also reduce the overall energy intensity of water treatment within the Denver Water service area. In 2008, water treatment has an average energy intensity of 307 kWh_{-eq} per million gallons. Under Alternative A, the energy intensity of treatment declines by 6% to 289 kWh_{-eq} per million gallons. Alternative C reduces the energy intensity of treatment to 252 kWh_{-eq} per million gallons.

[2] Denver Water uses a combination of electricity, natural gas, and diesel fuel to power its system. Here, we convert these energy sources into megawatt-hour equivalents to allow for comparison across scenarios.

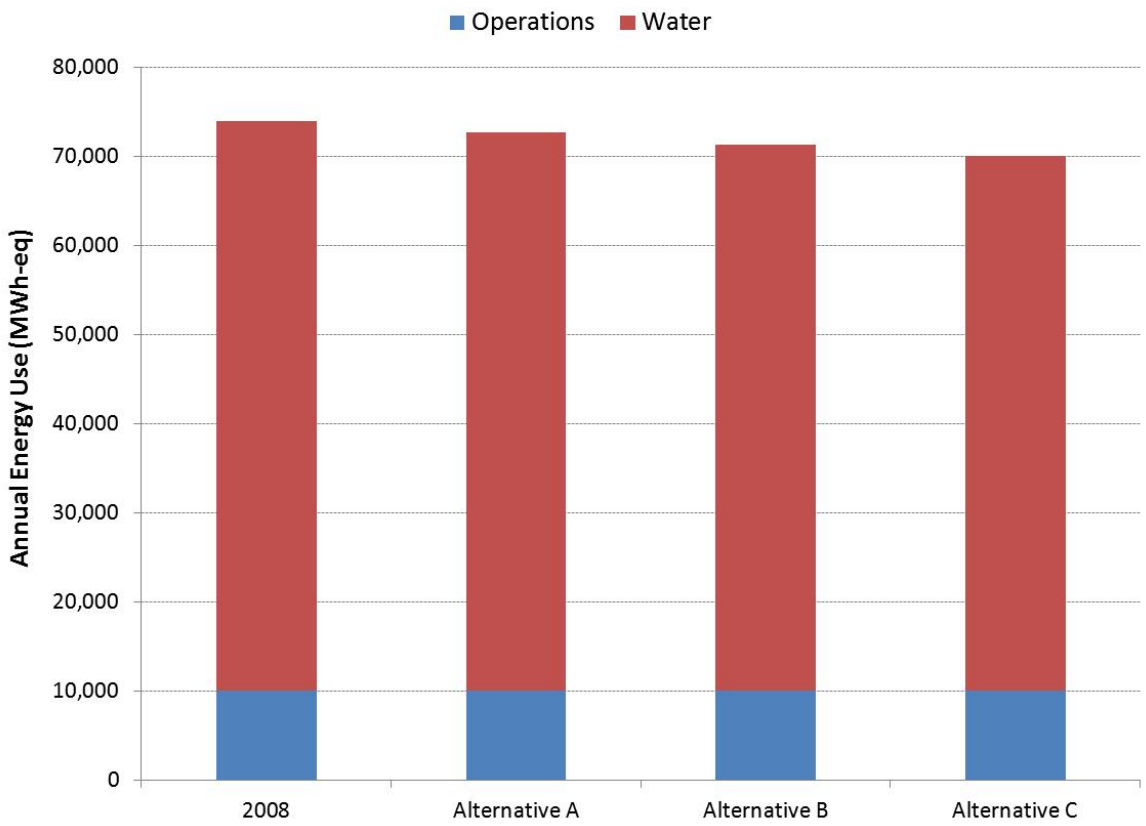

Figure 5.5. Annual energy requirements in 2008 and in Scenarios A, B, and C.

Note: Denver Water uses a combination of electricity, natural gas, and diesel fuel to power its system. Here, we convert these energy sources into MWh equivalents to allow comparison across scenarios.

The results indicate that shifting water to the Moffat WTP reduces energy costs. The WESim model output includes the total energy use by fuel type (Table 5.6). Using average energy prices for 2008, we estimate that the total energy costs under the current operating regime are about $5.25 million (in year 2008 dollars). Under Alternative A, however, energy costs are $5.17 million. Under Alternative C, energy costs are $4.99 million, an annual savings of $269,000. Note that energy costs are variable, and the savings here refer to energy costs in 2008. If energy prices rise, then the potential financial savings are even larger. Thus, reducing energy use helps to reduce the variability in energy costs and exposure to energy price increases over time.

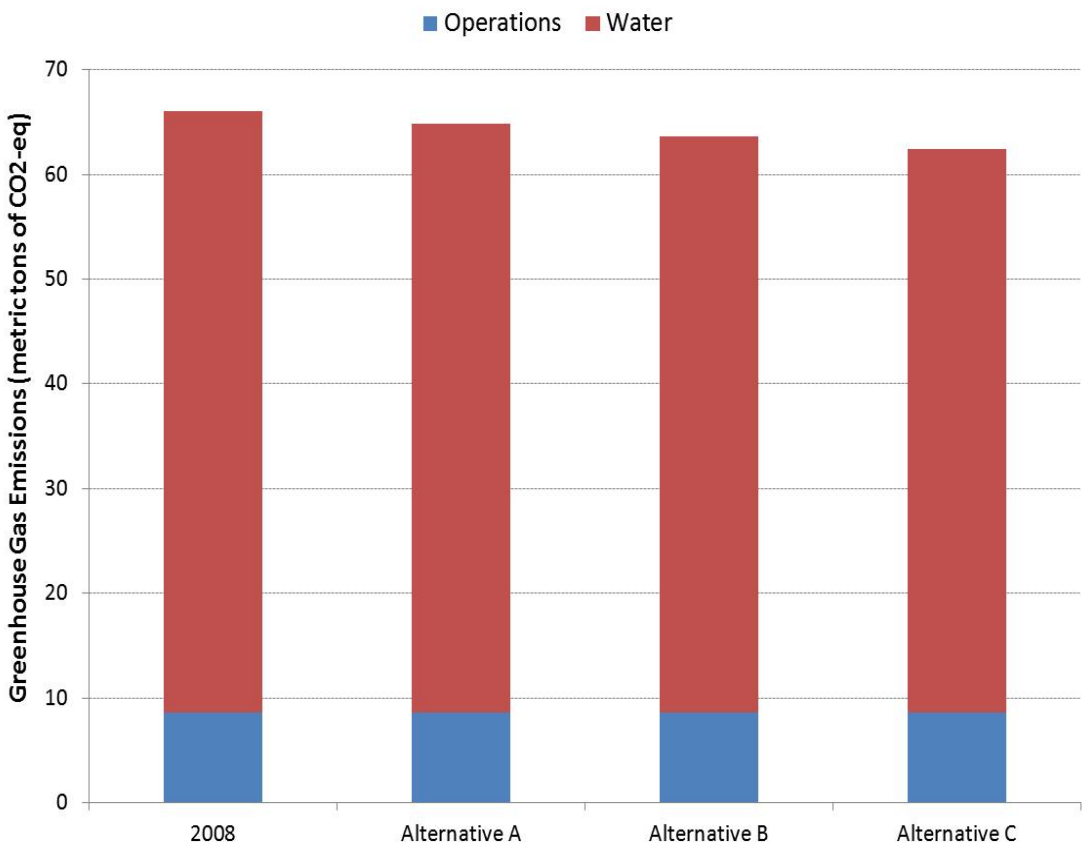

Figure 5.6. Annual greenhouse gas emissions in 2008 and in Scenarios A, B, and C.

The model results suggest that reducing flows at the Marston WTP while increasing flows to the Moffat WTP would reduce energy use, greenhouse gas emissions, and energy costs. It is important to note that these are preliminary results based on changes in flows for the water treatment only. They do not account for any changes in energy requirements associated with changes in the operation of the distribution system. It is possible that there would be system inefficiencies from the flow shift between plants that are not accounted for in these scenarios but should be considered in a more complete analysis.

Table 5.6. Total Electricity, Natural Gas, and Diesel Consumption in 2008 and in Scenarios A, B, and C

	Electricity (MWh)	Natural Gas (therms)	Diesel (gallons)	Estimated Energy Costs in 2008 ($ millions)
2008	66,435	815,549	5641	$ 5.25
Alternative A	65,148	815,549	5641	$5.17
Alternative B	63,817	815,549	5641	$5.08
Alternative C	62,500	815,549	5641	$4.99

Notes: Costs are shown in year 2008 dollars. Natural gas prices are based on average industrial prices in Colorado in 2008 ($0.85 per therm) from EIA. Electricity prices are based on average industrial prices in the United States in 2008 ($0.0683 per kWh). Diesel prices are based on average fuel prices in 2008 ($3.80 per gallon). All energy price data are from the U.S. Energy Information Administration.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

Water managers face increasing challenges and constraints in providing reliable, high-quality water supplies. Rapid population growth, emerging contaminants, rising costs, and climate changes are only some of these challenges. New tools are needed that can provide water managers and decision makers with useful information and facilitate quantification of alternative scenarios for decision support.

The Water-Energy Simulator (WESim) is an easy-to-use analytical tool that allows the user to evaluate the energy and greenhouse gas implications of population growth, the impacts of climate change, the development of alternative water and energy sources, needed water treatment improvements resulting from emerging contaminants and stricter water-quality guidelines, and changes in energy sources. The tool is suitable for individual water utilities and groups of water utilities, as well as policy and decision makers. The model has been designed to allow the user to input actual operating data for water and energy use, as this will allow an analysis that better reflects operating conditions. Defaults for the energy requirements of various components of the water and wastewater system have also been provided. However, one of the key findings of this effort is that adequate data on the energy requirements for water systems are lacking. In the following, we include a series of recommendations for improving the quantity and quality of data.

6.2 Recommendations

Energy requirements for the water and wastewater sector are still largely unknown. In recent years, numerous case studies have been undertaken to try to better quantify the energy requirements. However, these case studies are done in ways that are not directly comparable. For example, some studies lump all of the water and wastewater facilities together and report a single energy-intensity estimate. Others report energy intensity by category, e.g., treatment or distribution. Some studies report the treatment technologies employed, e.g., activated sludge, whereas others simply report the level of treatment, e.g., secondary or tertiary. The case studies also indicate that there is tremendous variability among water and wastewater systems. Often, the source of the variability is not analyzed.

- To develop more robust energy-intensity estimates, we recommend that a direct survey of water and wastewater utilities be initiated. The 2007 AwwaRF study provides a good model. These surveys should be done every five years in order to capture technological improvements and changing water quality conditions.
- The use of advanced treatment technologies is growing. However, these technologies are still relatively uncommon. As a result, energy requirements for these systems will not be captured well by direct surveys. Special effort will be needed to target treatment plants that employ advanced treatment technologies.

- Data on energy requirements for recycled water are also limited. We recommend that detailed surveys be conducted to target recycled water producers and distributers across the nation. Such a survey should identify source and product water quality, the size of the facility, and the treatment methods employed. Energy requirements for distributing recycled water should also be included in the survey.

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The Water–Energy Simulator (WESim)

User Manual

About the WateReuse Research Foundation

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

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

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

The Water-Energy Simulator (WESim)

User Manual

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Acronyms

AWWARF	American Water Works Association Research Foundation (now the Water Research Foundation)
$CO_{2\text{-eq}}$	carbon dioxide equivalents
eGRID	Emissions and Generation Resource Integrated Database
EPA	U.S. Environmental Protection Agency
PAC	Project Advisory Committee
RAC	Research Advisory Committee
VBA	Visual Basic for Applications
WESim	Water–Energy Simulator

Foreword

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

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

- Definition of and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

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

Water management decisions can have significant energy impacts. Water use entails energy in all phases, from collection to treatment to distribution to use to wastewater treatment. Multiple factors will influence the energy intensity of the water sector in the near future: climate change will affect water supply, quality, and demand, potentially creating a need for new water supply options; population growth, water use patterns, technology, and price all affect water demand; and emerging contaminants may require more energy-intensive treatment technologies. The Water–Energy Simulator (WESim) is an easy-to-use analytical tool that can be applied by water agencies, municipalities, and decision makers to evaluate the energy and greenhouse gas implications of water management decisions.

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Chair
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Chapter 1

Introduction

Water provision and use require energy in all phases, from source extraction to the discharge of wastewater. First, water is taken from a source and delivered to a community. In some cases, the force of gravity is sufficient; but in many cases, water must be pumped from groundwater wells or over long distances and steep terrain. Water must then be treated to drinking water standards through a variety of processes that require energy, including filtration, sedimentation, and disinfection. Treated water is then delivered to the tap, either by gravity or by additional pumping. Even more energy is used in homes, businesses, and institutions to heat, cool, purify, and pump water. Water that is used indoors must then be returned, and in some cases pumped, to a wastewater treatment facility, where it undergoes further processing that requires energy. Treated wastewater then either is returned to the environment by gravity or pumping or undergoes additional processing and is reused.

Multiple factors will influence the energy intensity of the water sector in the near future: climate change will affect water supply, quality, and demand, potentially creating a need for new energy-intensive supply and treatment options; population growth, water use patterns, technology, and price all will affect water demand; and emerging contaminants may require more energy-intensive treatment technologies. These trends highlight the need for a clear and consistent methodology for evaluating the energy and greenhouse gas implications of water management decisions.

The Pacific Institute and Dr. Bob Wilkinson, with support from the WateReuse Research Foundation, the California Energy Commission, the Canada Mortgage and Housing Corporation , and the Bureau of Reclamation, have developed the Water–Energy Simulator (WESim) as an easy-to-use analytical tool that can be applied by water and energy managers, municipalities, and decision makers. The model allows the user to evaluate the energy and greenhouse gas implications of population growth, the impact of climate change, the development of alternative water and energy sources, and needed water treatment improvements resulting from emerging contaminants and stricter water-quality guidelines. The tool is suitable for individual water utilities, groups of water utilities, and policymakers and decision makers.

WESim does not provide “the answer.” Rather, it is a tool that creates a common framework in which you can explore alternative scenarios. For example, you can compare the energy and greenhouse gas implications of using recycled water and of seawater desalination. Alternatively, you can explore the implications of installing ozone disinfection at a water treatment facility or biogas recovery at a wastewater treatment facility. You can also evaluate ways to offset the energy use and greenhouse gas emissions associated with energy-intensive water sources through the installation of renewable energy technologies or investments in conservation and efficiency.

The model is designed to allow you to input actual operating data on water and energy use, as this will allow an analysis that better reflects operating conditions. However, we recognize that not all users will have this information. To facilitate use of the model, we provide defaults for the energy requirements of various components of the water and wastewater

system. Detailed information about the structure and design of WESim can be found in the accompanying main report.

Chapter 2
Terminology

2.1 Water System Components

The model uses a basic analytical approach developed by Dr. Robert Wilkinson (2000) of the University of California at Santa Barbara (and refined and improved upon by a number of experts), which divides the water cycle into the stages shown in Figure 2.1. We suggest grouping facilities into the following system components:

- *Source extraction* refers to the extraction of water from a source to the surface of the Earth. Energy requirements for water supply depend on the location of the water relative to the surface and the method of extraction. Using this definition, the energy intensity of water extraction for water that is already at the surface, for example, seawater, recycled water, or river water, is zero.
- *Water conveyance* refers to the transport of untreated water through aqueducts, canals, and pipelines from its source to a water treatment facility or directly to an end user. Energy requirements for conveyance depend primarily on the distance and net elevation through which it is pumped, as well as the efficiency of the pumps used.
- *Water treatment* refers to processes and technologies that treat water to potable water standards prior to its distribution to homes and businesses. The energy requirements for treatment depend on the quality of the source water and the technology employed to treat that water. For recycled water, the energy requirements include the incremental treatment required to bring treated wastewater to recycled water standards. The energy intensity of recycled water treatment depends on the level of treatment required prior to discharge and the additional treatment required to bring it to the appropriate standard for the intended customer.
- *Water distribution* refers to the transport of treated water (both potable and nonpotable water) to customers. As with conveyance, the energy intensity of distribution depends largely on the distance and elevation through which water is pumped, as well as the energy efficiency of the pumps.
- *Customer end use* of water refers to the multitude of ways in which we use water in residential, commercial, industrial, institutional, and agricultural settings, which include personal hygiene, dish and clothes washing, landscape and crop irrigation, process water, and equipment cooling. Energy use associated with customer water end use is typically associated with heating, cooling, water treatment (e.g., filtering and softening), circulation, and supplemental pressurization in high-rises.
- *Wastewater collection* refers to the movement of untreated wastewater from the end user to a wastewater treatment facility. The energy requirements for wastewater collection depend on local geography and pump efficiency.
- *Wastewater treatment* refers to the application of biological, physical, and/or chemical processes to bring wastewater to discharge standards. The energy requirements for wastewater treatment depend on the level of treatment and, because wastewater must be pumped throughout the treatment facility, on pump efficiency.

- *Wastewater discharge* refers to the movement of treated wastewater from a wastewater treatment facility to the receiving waters. Energy requirements for wastewater discharge depend on local geography and pump efficiency.

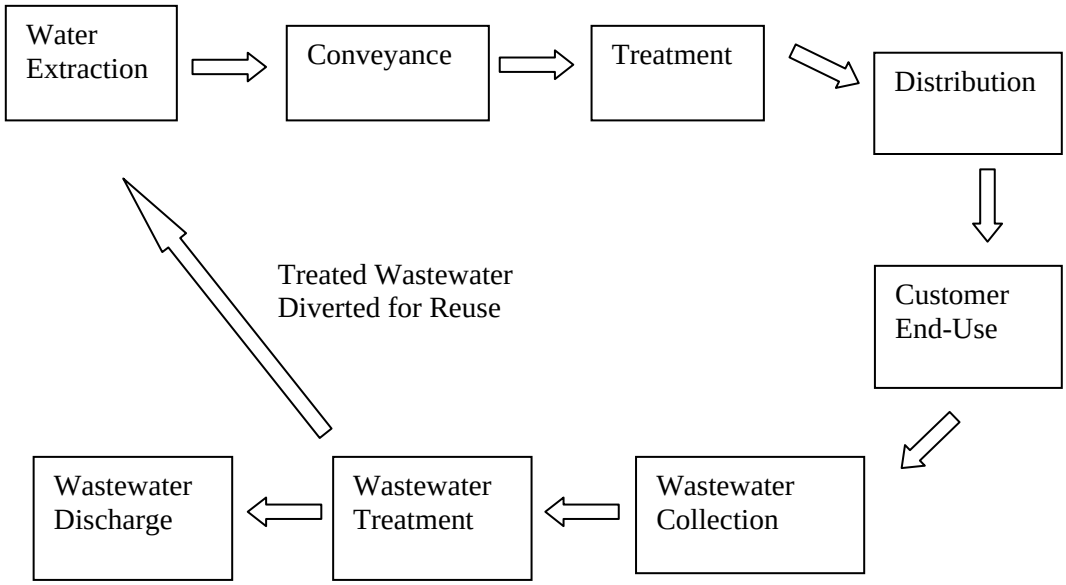


Figure 2.1. Flow diagram of water and wastewater systems.

Source: This schematic and method are based on Wilkinson (2000) with refinements by California Energy Commission staff and others.

Although these definitions set forth clear boundaries between the system components, in reality, these boundaries can be fuzzy. For example, an agency might pump high-quality groundwater from a well and add a small amount of chlorine at the well for disinfection prior to distribution to customers. In this case, the energy requirements for groundwater pumping and chlorine injection are likely captured by a single electricity meter. Thus, there is no way to distinguish between source water extraction and treatment. Using the WESim analytical framework, the user will have to classify the energy requirements as *either* source extraction or treatment. Either classification is acceptable; however, the user must be sure not to include the energy requirements as *both* source extraction and treatment, to avoid double counting.

The following example might assist you in thinking about your system using this framework. Say that a water agency operates a seawater desalination facility (Table 2.1). In this case, the energy intensity of water extraction is zero, because the water is already at the surface. Seawater is pumped from the ocean to the desalination facility, which requires an energy intensity of 50 kilowatt-hours (kWh) per million gallons (0.013 kWh per cubic meter). The seawater is then treated using reverse osmosis, which requires 15,000 kWh per million gallons (4.0 kWh per cubic meter). The treated water is distributed to customers, requiring 850 kWh per million gallons (0.22 kWh per cubic meter).

Table 2.1. Sample Desalination Facility

	Energy Intensity	
	kWh/m^3	**kWh/MG**
Source extraction	0	0
Conveyance	0.013	50
Treatment	4.0	15,000
Distribution	0.22	850

Notes: All numbers rounded to two significant figures. MG = million gallons; m^3 = cubic meters.

As a second example, consider recycled water. Say that we have a system where wastewater receives secondary treatment at the Smith Facility before it is discharged into the ocean using gravity. Some of the wastewater receives additional treatment at the Smith Facility to bring it to recycled water standards (Table 2.2). In this example, the recycled water is already at the surface and is not transported to another facility for the additional treatment it receives. Thus the energy intensity of water extraction and conveyance is effectively zero. The energy intensity of treatment is the additional energy required to bring the secondary-treated wastewater to recycled water standards, or 1100 kWh per million gallons (0.29 kWh per cubic meter). The recycled water must then be distributed to the end users, which is estimated to require 900 kWh per million gallons (0.24 kWh per cubic meter).

Table 2.2. Sample Recycled Water Facility

	Energy Intensity	
	kWh/m^3	**kWh/MG**
Source extraction	0	0
Conveyance	0	0
Treatment	0.29	1,100
Distribution	0.24	900

Note: All numbers rounded to two significant figures. MG = million gallons; m^3 = cubic meters.

2.2 Scenarios, Water Systems, and Water System Facilities

WESim uses scenario-based planning to model how changes to water systems will affect energy use and greenhouse gas emissions. WESim uses the concepts of water *systems*, water system *facilities*, and *scenarios* to model these changes. A water system facility is a facility, such as a well or treatment plant, or a group of facilities that are related, such as a well field. The water system is made up of any number of these facilities. Each scenario is a description of the water system under a certain set of conditions. Most users will begin by creating a scenario that represents current conditions, or the “baseline.”

For example, a small water agency extracts water from a local reservoir, provides treatment at a nearby facility, and distributes treated water to its customers. This agency also collects, treats, and discharges wastewater. The agency is considering recycling some of the wastewater to offset withdrawals from the local reservoir.

To begin with, you should first develop the Baseline Scenario, containing all of the existing water system facilities, including the pumps to convey raw water and wastewater to the treatment facilities, the water and wastewater treatment facilities, and the booster pumps to distribute treated water to the customers. Add as much detail as is available or appropriate. It requires time and effort to accurately and completely represent your water system. Once the Baseline Scenario has been completed, however, WESim is a powerful tool for envisioning possible water and energy futures.

After you have developed a Baseline Scenario, create a new scenario by duplicating the Baseline Scenario and renaming it "Baseline with Water Recycling." Then make the following adjustments to the water system that features recycling:

- reduce the volume of wastewater that is discharged;
- add a new source extraction facility called "recycled water";
- reduce the volume of surface water that is conveyed, treated, and distributed;
- add a new treatment facility, which captures the additional treatment required to bring the treated wastewater to recycled water standards; and
- add new facilities needed to distribute recycled water.

Once these changes to the new scenario have been made, you can view the model output and compare the overall energy consumption and greenhouse gas emissions between the "Baseline" and "Baseline with Water Recycling" scenarios. This example is illustrated in Figure 2.2.

Scenarios:	Baseline	Baseline with Water Recycling
System	Source Extraction Local surface water	Source Extraction **Local surface water** *Recycled water*
	Water Conveyance Raw water pumps	Water Conveyance **Raw water pumps**
	Water Treatment Treatment plant	Water Treatment **Treatment plant** *Recycled water treatment*
	Water Distribution Booster stations	Water Distribution **Booster stations** *Recycled water booster stations*
	End Use Commercial Industrial Residential	End Use Commercial Industrial Residential
	Wastewater Conveyance Sewer booster stations	Wastewater Conveyance Sewer booster stations
	Wastewater Treatment Wastewater Plant	Wastewater Treatment Wastewater plant
	Wastewater Discharge Gravity fed	Wastewater Discharge **Gravity fed**

Figure 2.2. Example of a simple simulation.

Note: The new components are shown in *italics*, and the modified components are shown in **bold**.

Chapter 3

Model Specifications

3.1 Minimum System Requirements

WESim is a Microsoft Excel workbook with a number of macros to facilitate data entry, calculation, and display of results. As you work, the information that you input will be stored in a Microsoft Access database file. The workbook is compatible with Excel 2000 and later versions on PC computers. WESim has not been tested on Macintosh computers. You must also have Microsoft Access installed on your computer.

3.2 About User Mode and Developer Mode

You may use the model in either user or developer mode.

User mode is suggested for most model users and is enabled by default. The user mode simplifies data entry, hides formulas, and displays one sheet at a time. You can return to user mode at any time by navigating to the Introduction page and clicking the “User Mode” button. It is also available at any time by typing Ctrl + Shift + U.

Developer mode allows you to “look under the hood.” The developer mode removes worksheet protection to make every cell selectable and shows all of the worksheets. It is available by clicking the “Developer Mode” button on the Introduction page or by typing Ctrl + Shift + R.

Even with the Excel workbook in developer mode, much of the program’s logic and calculations are done in Visual Basic for Applications (VBA) code. You can view the program using Visual Basic Editor. Please refer to the help manual within Excel for instructions on performing this operation.

Chapter 4

Getting Started

4.1 Model Overview

Here, we provide a general overview of the steps required to use the model. For additional information on each step, please refer to the section indicated.

1. Open WESim in Excel and enable macros (see Section 4.2 for instructions).
2. Establish a working file on the *Start Page* (see Section 5.1 for instructions).
3. Create a new scenario on the *Scenario Manager* page (see Section 5.2 for instructions). Click on the button that shows the name of the scenario you would like to edit to go to the *Water System Manager* page.
4. On the *Water System Manager* page, begin adding water and wastewater system facilities to the scenario (see Section 5.3 for instructions).
5. On the *Water System Facility Editor* page, add details about each facility, including its name, classification, flow, and energy use (see Section 5.4 for instructions).
6. On the *Energy Source Manager* page, edit your energy sources; include all of the energy sources that power your system (see Section 5.5 for instructions).
7. Add additional scenarios by repeating steps 3–6.
8. Once you have entered all of the scenarios, review the model output (see Section 6.1 for instructions).

4.2 Enabling Macros

This workbook contains custom VBA macros. Most Excel programs, however, have security settings that will not allow macros. To use WESim, you must change the Excel security settings. Detailed instructions for changing the security settings can be found in Section 4.2.1. *Please note that you will only need to change the security settings once.* Once you have changed the security settings, you can enable the macros by following the procedure outlined in Section 4.2.2.

4.2.1 Changing the Security Settings

This workbook contains custom VBA macros that must be enabled when opened. To enable macros, you must first change the security settings on Excel. You will only need to do this once. To change the security settings, follow the outlined procedure for the version of Excel that you are using. Note that you should not have the WESim Excel file open while changing the security settings.

Excel 2000–2003 (including Office XP)

(1) In Excel, choose Tools > Macro > Security.
(2) In the Security window, choose "*Medium*" and click "*OK*." *You have now changed the security settings of Excel. You will only need to perform these steps once.*

Excel 2007

(1) Click the File tab or round Office Button ( ) at the upper left of the screen, and then click "*Excel Options*," which is located at the bottom of the window.
(2) Within the Excel Options window, select the Trust Center tab on the left. Click the button "*Trust Center Settings*" (Figure 4.1).
(3) Under the Macro Settings tab, select "*Disable all macros with notification*," and click "*OK*" (Figure 4.2). Click "*OK*" again to save your Excel options. *You have now changed the security settings of Excel. You will only need to perform these steps once.*

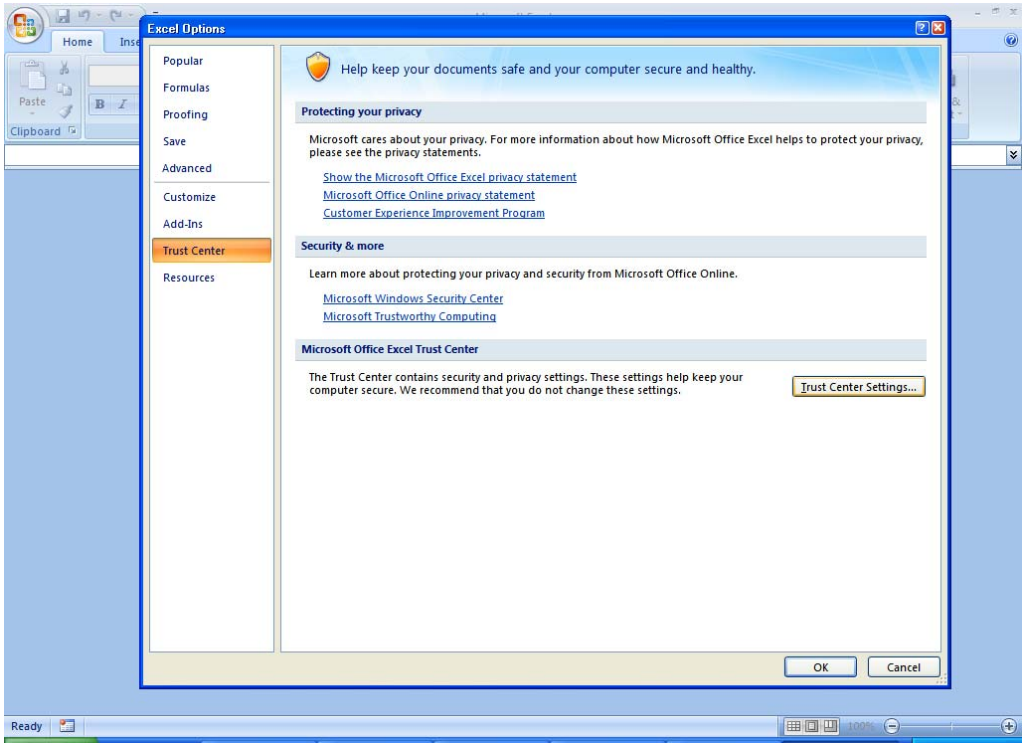


Figure 4.1. Changing the trust center settings.

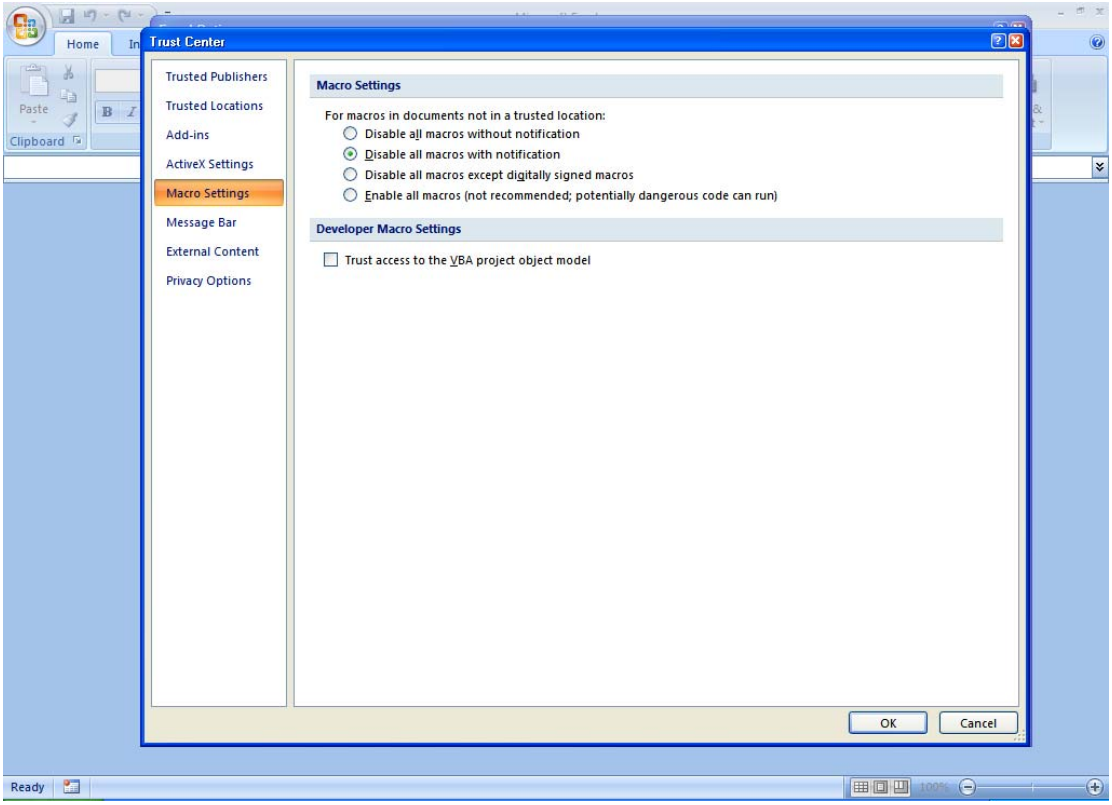


Figure 4.2. Changing the macro settings.

4.2.2 Enabling Macros

Enabling macros requires slightly different procedure depending on the version of Excel that you are using. Directions are provided below for Microsoft Excel 2000–2003 and Excel 2007. For other versions of Excel, please refer to the help file within Excel for direction on enabling macros.

Excel 2000–2003 (including Office XP)

(1) Download WESim to your computer. Open the WESim Excel file.
(2) A pop-up dialog box will appear.
(3) Click the button to Enable Macros. You will need to repeat this step every time you open WESim.

Microsoft Excel 2007

(1) Download WESim to your computer. Open the WESim Excel file.
(2) A message bar will appear near the top of the Excel window, titled “Security Warning.” Click the “*Options* . . .” button (indicated by the arrow in Figure 4.3).
(3) In the Microsoft Office Security Options window, choose “Enable this content” and click “*OK*” (Figure 4.4). You will need to do this step every time you open WESim.

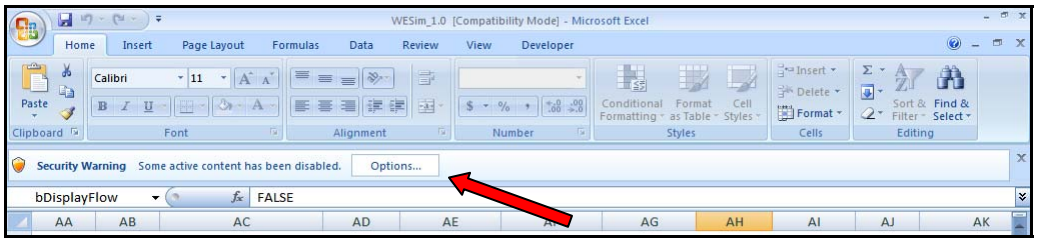


Figure 4.3. Security warning panel in Excel 2007.

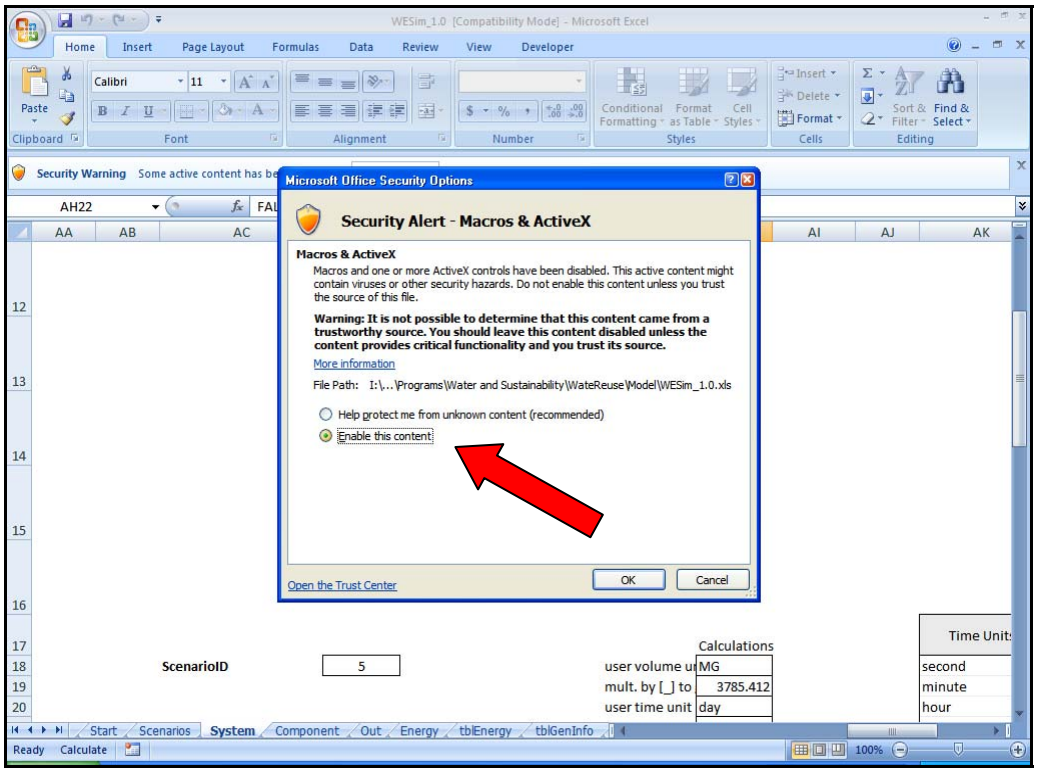


Figure 4.4. Enabling macros in Excel 2007.

Chapter 5

Model Inputs

Once you have enabled the macros, you can begin using WESim. You will enter information on five worksheets: (1) the *Start Page, (2)* the *Scenario Manager*, (3) the *Energy Source Manager*, (4) the *Water System Manager*, and (5) the *Water System Facility Editor*. Inputs for each worksheet are described in the following sections.

5.1 Start Page

The Start Page contains the basic data file management tasks (Figure 5.1). You must first set up a working database, where responses will be stored as worksheets are completed. To create a new database, click "**Create a New File**." Select the country where the facilities are located; your selection here will determine the units used throughout the model, as well as default values for the greenhouse gas emissions associated with various fuels in Canada and the United States and the electricity grid loss factors (see Section 5.5 and Cooley et al., 2012 for additional information). Once you have selected the appropriate country, specify a file name and location and click "**Save**." You are free to save this file anywhere on your computer or local network. WESim will set up this new file as the current working database. Do not move or delete the working database file while using the model. To continue working with a previously created scenario, click "**Open an Existing File**" and navigate to the appropriate Access database (.mdb) file. As you navigate from one sheet to another, responses are automatically saved in the database file.

After you have established a working file, you may begin creating your baseline scenario by proceeding to the Scenario Manager page. Go to the Scenario Manager page by selecting the "**Scenario Manager**" hyperlink at the top of the screen or on the navigation panel (Figure 5.1). Instructions for adding scenarios can be found in Section 5.2.

A number of data file management tasks can be accessed from the Start Page. In addition to creating a new or opening an existing file, you can do the following:

- From time to time, you may wish to make a backup of your current data file to return to a particular set of inputs at a later time. "**Duplicate the Current File**" will make a copy of the active database file with a name you specify.
- If you work with a single database file for a while, the file size will steadily increase. From time to time, you may wish to click "**Compact Database File**." This step is not mandatory, but may result in slightly faster performance.
- Click "**Check Database Connection**" to verify that the file shown is a valid WESim database. You will likely never need to use this button.
- Click "**View Folder**" to open Windows Explorer and identify the directory where your database file is stored. This may be useful for managing or moving your data files.
- Click "**Clear This Sheet**" to remove all of your entries from the page.

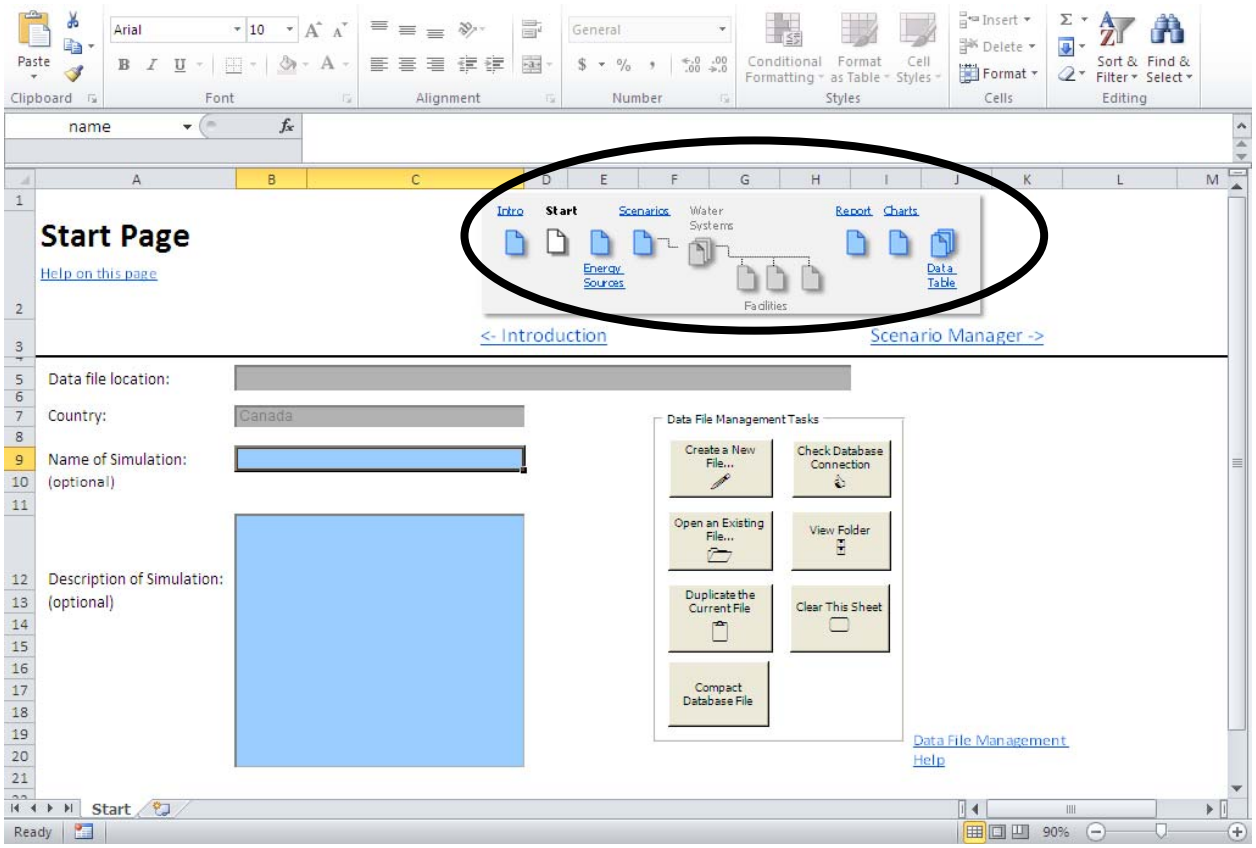


Figure 5.1. Model start page with navigation panel circled.

5.2 Scenario Manager

On the Scenario Manager page, you can create up to 10 different scenarios (Figure 5.2). To get started on the Scenario Manager page, click the "**Add a Scenario**" button in the Scenario Management section. Type a name for the scenario when prompted—for example, "Baseline." This scenario will appear as a button. Once you have created your first scenario, click on the scenario button to go to the Water System Manager page, where you can begin entering information about the various facilities within your water/wastewater system.

Depending on the level of detail you wish to enter, modeling the system and adding all of the necessary information can be time-consuming. Once you have filled in the water system to your satisfaction, you can create a carbon copy of it that you can easily modify. To do this, click the "**Duplicate Scenario**" button and choose the scenario to copy. Enter a new scenario name and click "**OK**." A button will appear on the Scenario Manager page with the new scenario name. Click on the scenario button to go to the Water System Manager page, where you make changes to existing facilities or add new facilities.

You can also delete or rename scenarios, and move them up and down in the list by clicking "**Change Order**." *Please note that deleting a scenario is permanent and there is no way to undo this.*

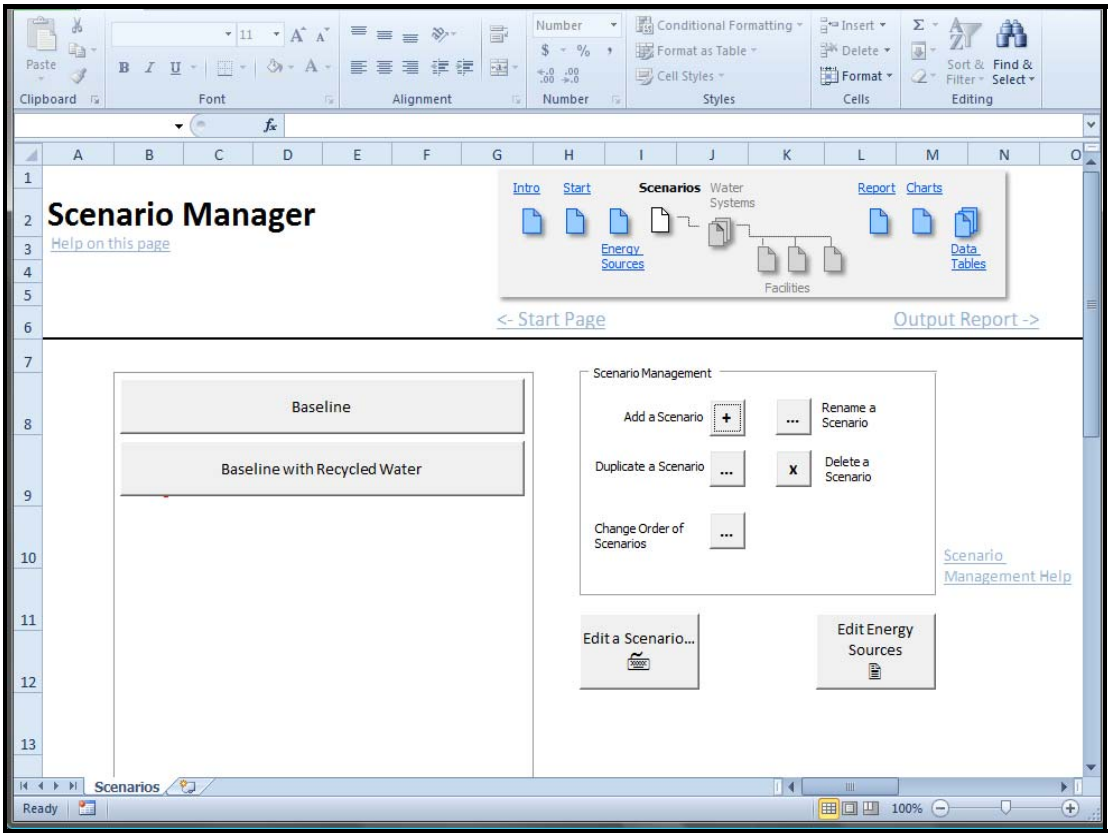


Figure 5.2. Scenario manager page.

5.3 Water System Manager

The Water System Manager is where you can build a water system by adding, deleting, or duplicating system facilities such as groundwater wells, conveyance systems, or water treatment facilities (Figure 5.3). WESim allows you to add as much detail as you wish, or as is appropriate for your agency. For example, you can enter data for each groundwater well by making each well a separate facility, or for all wells combined. Likewise, you can enter information on each section of the water distribution system or for all sections of the water distribution system combined.

To begin, click the "**Add a Facility**" button in the Facility Management section. You will then be taken to the Water System Facility Editor page, where you can begin filling in information on the water system facility and its water and energy use (see Section 5.4 for instructions). Once you have created a facility, it will appear as a button on the Water System Manager page. You can edit information about this facility by clicking on this button.

On the Water System Manager page, you have the option to display the water volume and energy use for system facilities by clicking the checkboxes near the top of the sheet. You can also choose from a wide range of units. WESim will automatically convert the results and display them on the sheet in the units you select. The numbers in blue correspond to water flow, while the numbers in red correspond to energy usage.

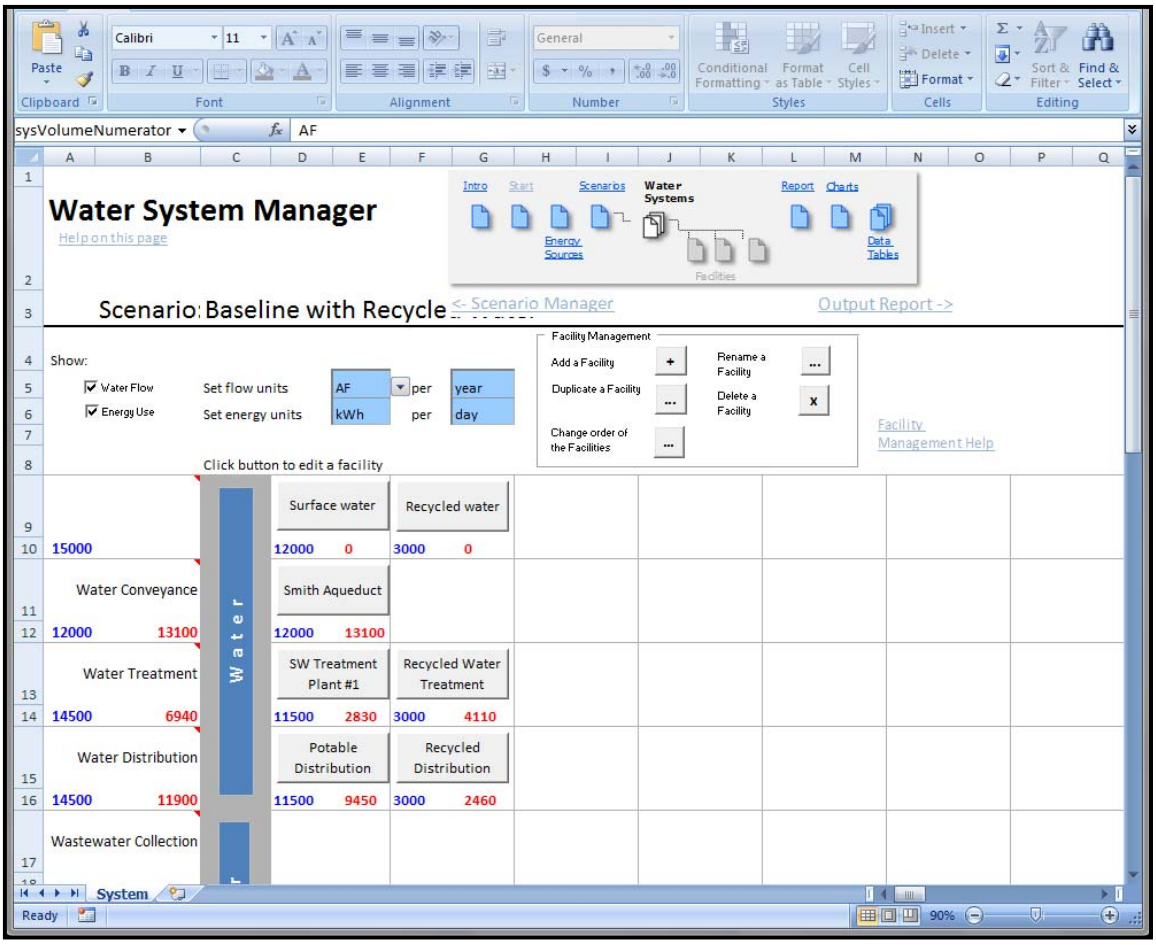


Figure 5.3. Water system editor page.

If the numbers displayed under a component button look like this, #####, then the number is too large to be displayed in the cell. Try changing the units of time in the denominator, for example, from “per month” to “per day” or “per year.” Large numbers will be displayed in scientific notation (1.34E+09), and smaller numbers will take less room to display.

5.4 Water System Facility Editor

The Water System Facility Editor page is where you specify the water flow and energy use for a particular facility (Figure 5.4). Before entering water system facilities, be sure you have entered all of the energy sources that power your water and wastewater system into the Energy Source Manager. If you have not already done this, select “**Edit Energy Sources**” to go to the Energy Source Manager page (for additional instructions on this page, see Section 5.5). After you have finished entering the energy sources, select “**Save**” to return to the Water System Facility Editor page.

Once you have entered all of the energy sources, begin by naming the facility and selecting whether it represents extraction, conveyance, treatment, distribution, end use, wastewater collection, wastewater treatment, or wastewater discharge. You should then indicate the volume of water that is conveyed through or treated at the facility. You can enter the actual energy consumption of the facility or some estimate of its energy intensity. Because a single

facility may be powered by multiple energy sources, e.g., electricity plus a natural gas–powered backup generator, WESim allows you to enter up to five different energy sources for a single facility. Note that you will *not* be able to save the facility if data are missing or filled out incorrectly.

Actual energy use may be found on electric and gas bills or meter records. Bills for electricity are usually expressed in kWh or megawatt-hours (MWh), and natural gas is often billed in units of therms. WESim offers you a number of choices of units for entering data. You should use some caution when using a bill from a single month, or meter readings for a day or week, especially if water demand varies seasonally. We suggest collecting a year's worth of bills and entering an annual total.

Some users may not have access to this information. To assist these users, WESim provides default values for a number of water system facilities. To develop default values, we conducted an extensive literature review of energy intensity values for each stage of the water use cycle, e.g., water extraction, water conveyance, water distribution, customer end use, wastewater collection, wastewater treatment, and wastewater discharge. A preliminary analysis of the data revealed significant variability among water and wastewater systems. In many cases, additional information was not available to determine the cause of this variability, e.g., the size of the facility or the various treatment processes employed. Detailed surveys of water and wastewater utilities are needed to develop more robust energy intensity estimates. Such an effort, however, was beyond the scope of this project.

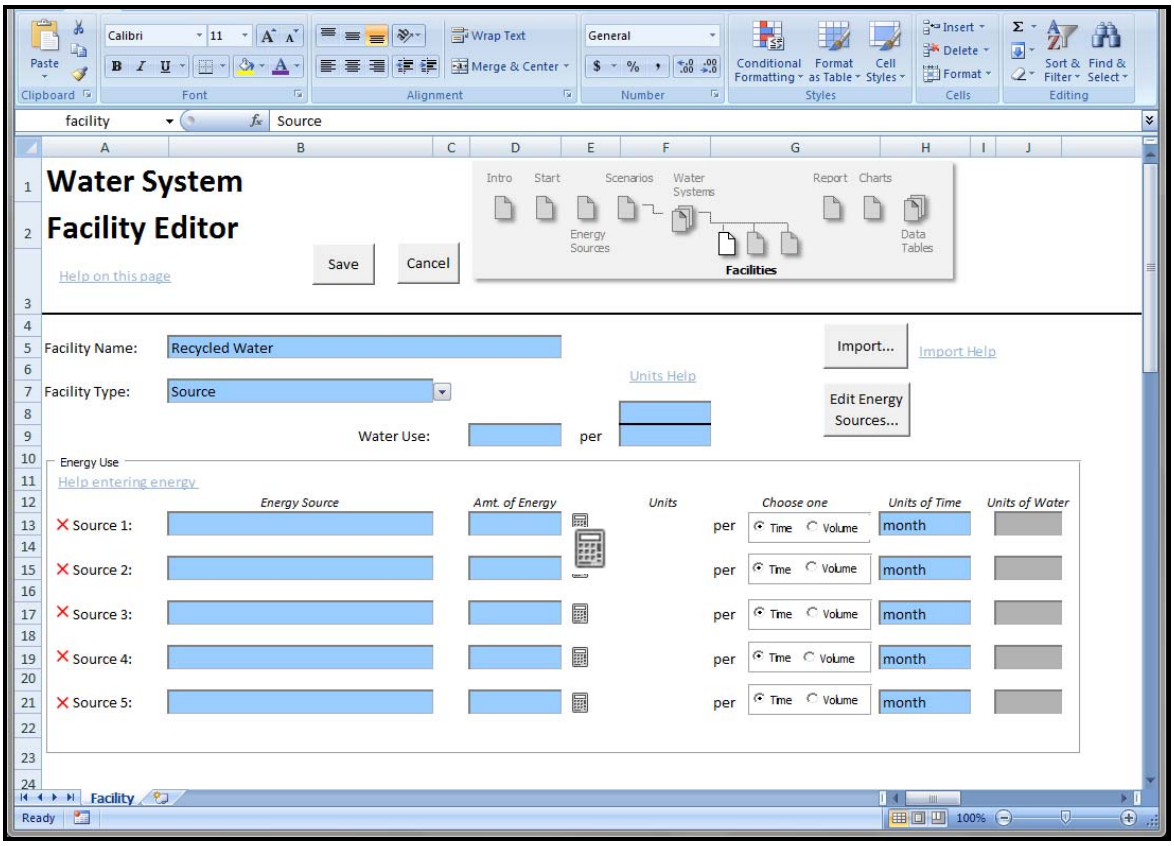


Figure 5.4. Water system facility editor page.

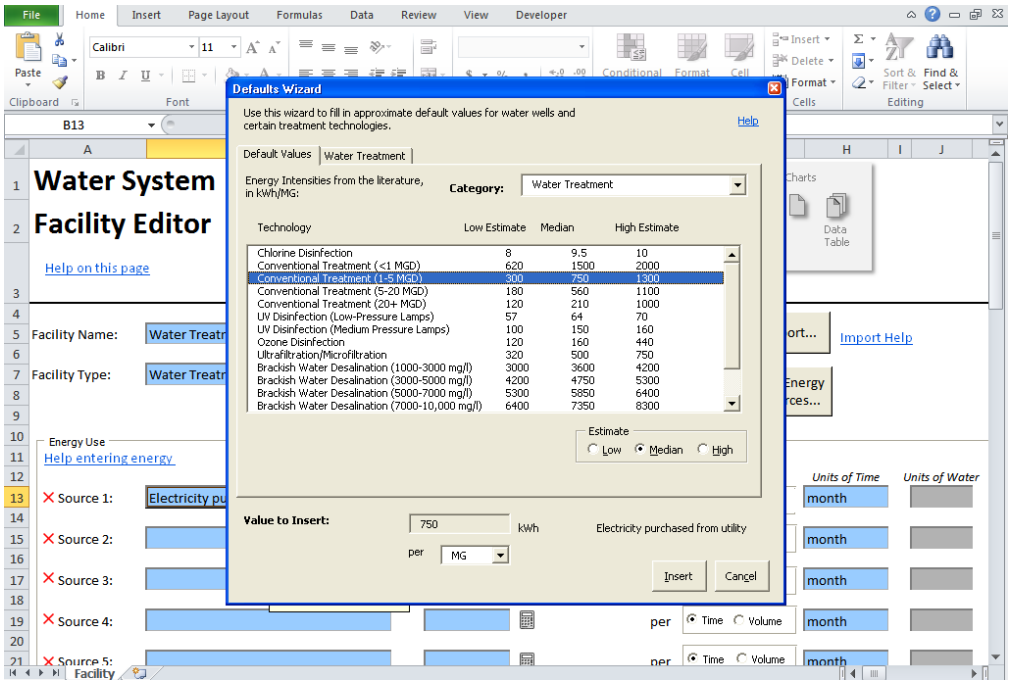


Figure 5.5. WESim default wizard.

During the course of the literature review, we identified a comprehensive study funded by the AWWA Research Foundation (AWWARF), the California Energy Commission, and the New York State Energy Research and Development Authority that was designed to develop an energy index for benchmarking water and wastewater utilities (AWWARF, 2007). Data were gathered from 266 wastewater treatment plants and 125 water utilities, and regression analyses were performed to test the correlation of various system parameters and energy use. These regression equations have been adopted by the U.S. Environmental Protection Agency (EPA) in its benchmarking tool for water and wastewater utilities and have been integrated into WESim.

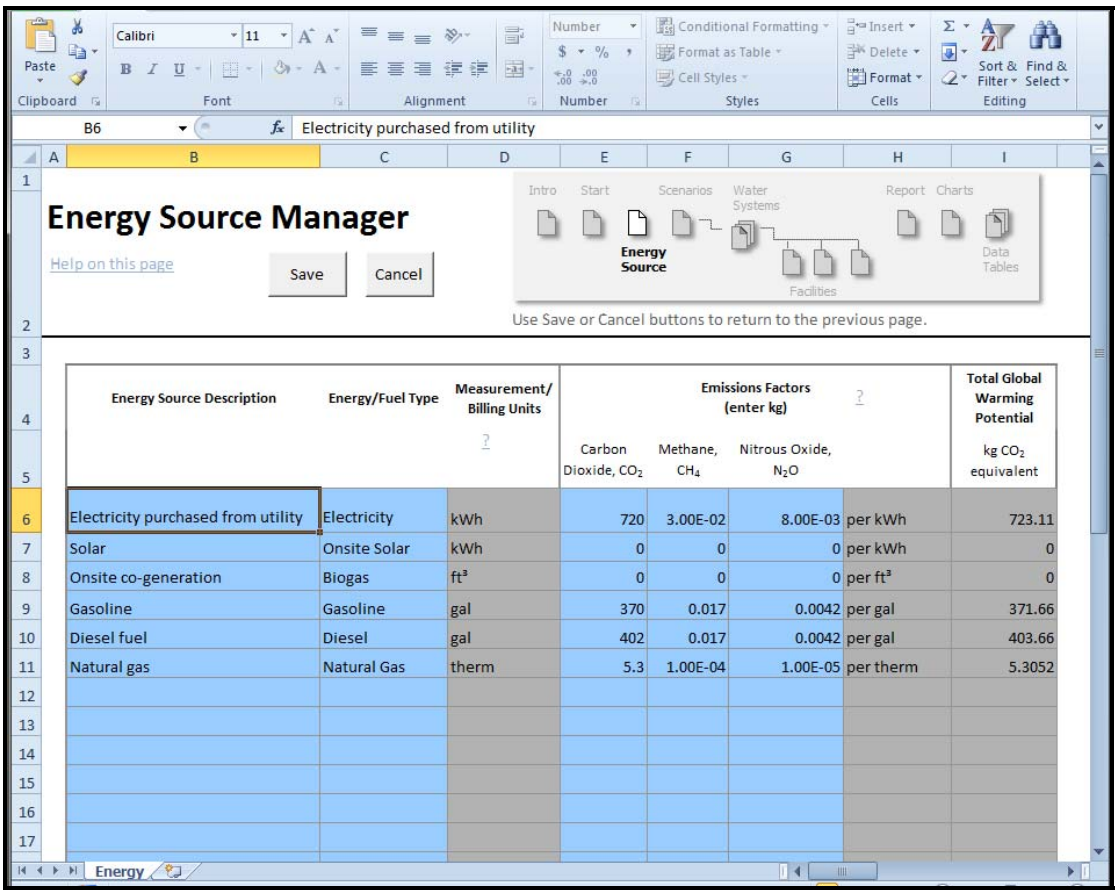
To provide additional flexibility, WESim allows you to use a default value from the literature or one estimated by entering information into the regression equation to produce a more customized estimate. To look up a default value, click the small calculator button ( ) next to the energy input. A default wizard will appear (Figure 5.5). To access the default values from the literature, choose the Default Values tab. Defaults are organized by the component of the water and wastewater system (e.g., source, treatment, distribution, wastewater collection). Choose a category and then select the appropriate default value. Indicate whether you would like to use the low, median, or high value and click "**Insert**." Great care should be exercised here, as average values from the literature often vary widely. The conscientious modeler should run the simulation several times, using combinations of high and low estimates and observing the impact on the results.

To use the regression equation, select the water system category and click on the tab with the category name. Fill in the required information based on your water/wastewater system. Once you have entered the information, click "**Insert**." The model defaults for each of the water and wastewater system components are described in greater detail in Cooley et al. (2012).

5.5 Energy Source Manager

The Energy Source Manager is where you can enter information on the energy sources that power your system and the associated greenhouse gas emissions factors. Water and wastewater systems may be powered using a variety of energy sources, including electricity purchased from a third party, self-generated electricity, natural gas, and diesel fuel. Even a single facility may be powered by a multitude of sources. For example, a wastewater treatment plant may use biogas recovery to offset some of its electricity use, purchase electricity from a third party, and operate a diesel-powered backup generator.

WESim allows you to enter all of the energy sources that power the water and wastewater system and evaluate how changes in the energy mix affect greenhouse gas emissions. On the Energy Source Manager page, enter every energy source that powers your water and wastewater system (Figure 5.6). This information should include electricity purchased from third parties and fuels used on site to produce electricity, heat, or motive power. For each energy source, identify whether it is natural gas, off-site electricity, on-site electricity, diesel, propane, residual fuel oil, or gasoline.



Energy Source Description	Energy/Fuel Type	Measurement/ Billing Units	Emissions Factors (enter kg) Carbon Dioxide, CO_2	Methane, CH_4	Nitrous Oxide, N_2O		Total Global Warming Potential kg CO_2 equivalent
Electricity purchased from utility	Electricity	kWh	720	3.00E-02	8.00E-03	per kWh	723.11
Solar	Onsite Solar	kWh	0	0	0	per kWh	0
Onsite co-generation	Biogas	ft^3	0	0	0	per ft^3	0
Gasoline	Gasoline	gal	370	0.017	0.0042	per gal	371.66
Diesel fuel	Diesel	gal	402	0.017	0.0042	per gal	403.66
Natural gas	Natural Gas	therm	5.3	1.00E-04	1.00E-05	per therm	5.3052

Figure 5.6. Energy source manager page.

Table 5.1. Greenhouse Gas Emissions Factors for Various Fuels and for Electricity

Fuel Type	Energy Unit	Emissions Factors (kg/energy unit)		
		Carbon Dioxide (CO_2)	Methane (CH_4)	Nitrous Oxide (N_2O)
Electricity (avg. U.S. grid)	kWh	0.588	1.14×10^{-5}	8.93×10^{-6}
Electricity (avg. Canadian grid)	kWh	0.206	9.00×10^{-6}	4.00×10^{-6}
Solar	kWh	0	0	0
Onsite cogeneration	ft^3 or m^3	0	0	0
Gasoline	gal	8.780	1.40×10^{-3}	1.00×10^{-4}
Gasoline (Canadian metric)	L	2.289	1.2×10^{-4}	1.6×10^{-4}
Diesel fuel	gal	10.21	1.50×10^{-3}	1.00×10^{-4}
Diesel fuel (Canadian metric)	L	2.663	1.33×10^{-4}	4.00×10^{-4}
Natural gas (United States)	therms	5.302	1.00×10^{-4}	1.00×10^{-5}
Natural gas (Canadian metric)	m^3	1.881	3.70×10^{-5}	3.5×10^{-5}

Source: Tables G1, G11, and G19 in CARB (2010); Table A1 in EPA (2008); and Environment Canada (2010a,b).

Notes: Natural gas emissions for Canada were based on average of Canadian provinces (except Northwest Territories) in Environment Canada (2010b). Electricity emission factors are based on average grid in the United States and Canada in 2007 from Table A1 in EPA (2008) and Environment Canada (2010a).

For each energy source, you must also enter its greenhouse gas emission factor**,** which represents the amount of greenhouse gas emissions per unit of fuel or energy consumption. Default greenhouse gas emission factors are provided for some energy sources, including solar, cogeneration, ethanol, natural gas, and diesel fuel (Table 5.1). In some cases, as with electricity and natural gas, there is regional and/or temporal variation in these factors. WESim allows you to enter custom emission factors to account for alternative energy sources and any changes in the emissions factors over time. Enter additional energy sources as appropriate for your system by entering the information as a new line in the table on the Energy Source Manager page.

The default emission factors for electricity are based on the average U.S. grid in 2007 and the average Canadian grid. These values should be used with great caution. The greenhouse gas emissions associated with electricity use are driven by the types of fuels that are used to generate the electricity, which varies regionally and temporally. In addition, as energy utilities alter their fuel mixes to meet renewable portfolio standards and goals, the greenhouse gas emissions factors will change. Therefore, emission factors that are specific to your area, and that correspond for the year for which you are reporting data, should be used whenever possible.

Electricity emissions data can be accessed from a variety of sources. These data are typically either regional or utility-specific values. When possible, utility-specific values should be used since the regional data do not capture local variability in emission factors. Users can contact their local electricity providers to obtain appropriate emission factors. Third-party verified emission factors for electricity providers that are members of the California Climate Action Registry can be found in Table G.6 in California Air Resources Board (2010), at http://www.theclimateregistry.org/downloads/2010/05/2010-05-06-LGO-1.1.pdf.

It is not yet standard for utilities to calculate and verify their emission factors. In the absence of these data, regional electricity emission factors may be needed. These regional estimates can be found at the following:

1. The EPA produces the Emissions and Generation Resource Integrated Database (eGRID), a comprehensive data source for electricity emission factors for 26 subregions across the United States. These data are updated periodically to better reflect changes in emissions from the U.S. electricity grid. The newest version, released in February 2011, provides data for the year 2007. The eGrid data can be found in EPA (2011), at http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2010V1_1_year07_SummaryTables.pdf.

2. For Canada, province-level data are available in Environment Canada (2010a), at http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=EAF0E96A-1#section1.

3. For all other countries, emission factors for electricity production can be found in IEA (2010), at http://www.iea.org/co2highlights/CO2highlights.pdf.

Greenhouse gas emission factors for primary fuels are much less variable than those for electricity. However, in some cases, as with natural gas, there is some regional variation. Additional factors for primary fuels can be found in a variety of locations, including Environment Canada (2010b) and California Air Resources Board (2010).

Chapter 6

Model Outputs

Model outputs include energy use and greenhouse gas emissions for each alternative scenario (Figure 6.1). You can select among a range of units for viewing the outputs. Outputs are provided in tabular and graphical form and can be exported for use in other programs, such as Microsoft® Word, Excel, and PowerPoint, and webpages for use in reports and presentations.

Energy use outputs include both source and site energy. Site energy is the sum of the various energy sources used to power a water or wastewater system. Site energy units typically include kWh of electricity, therms of natural gas, and gallons of liquid fuels. Because these energy uses are reported in different units, it is difficult to compare across scenarios. How, for example, does 5 therms of natural gas compare to 125 kWh of electricity? Furthermore, there are different conversion efficiencies associated with each of the energy sources. Although site energy may not be useful for comparing total energy requirements for alternative scenarios, site energy values can be useful for other analyses. For example, a scenario may result in the use of 125,000 kWh of electricity, 550 therms of natural gas, and 5200 gallons of diesel fuel. These data are provided in tabular form, allowing the user to combine the output with other information, such as current and projected energy prices, to evaluate energy cost trends and sensitivity to changes in energy price over time.

Source energy provides a means to compare scenarios that contain facilities powered by a variety of energy sources. Source energy is the total amount of raw fuel that is consumed to operate the facility (including fuel used to produce electricity off site). Water and wastewater facilities commonly use a combination of energy sources; some of these energy sources (natural gas, diesel, and biogas) are primary energy sources, meaning that the raw fuel is consumed onsite to produce heat or electricity. Electricity, on the other hand, is a secondary energy source because it is the product of a raw fuel burned elsewhere. Because different energy sources are measured in different units and have different efficiency losses associated with them, calculating total system energy use requires converting the diverse energy sources into comparable units. WESim reports source energy in units of British Thermal Units (Btu) and kilojoules (kJ). Because most energy managers are familiar with units of electricity, WESim converts all of the source energy into site energy and reports in units of kilowatt-hour equivalents (kWh_{-eq}) and megawatt-hour equivalents (MWh_{-eq}).

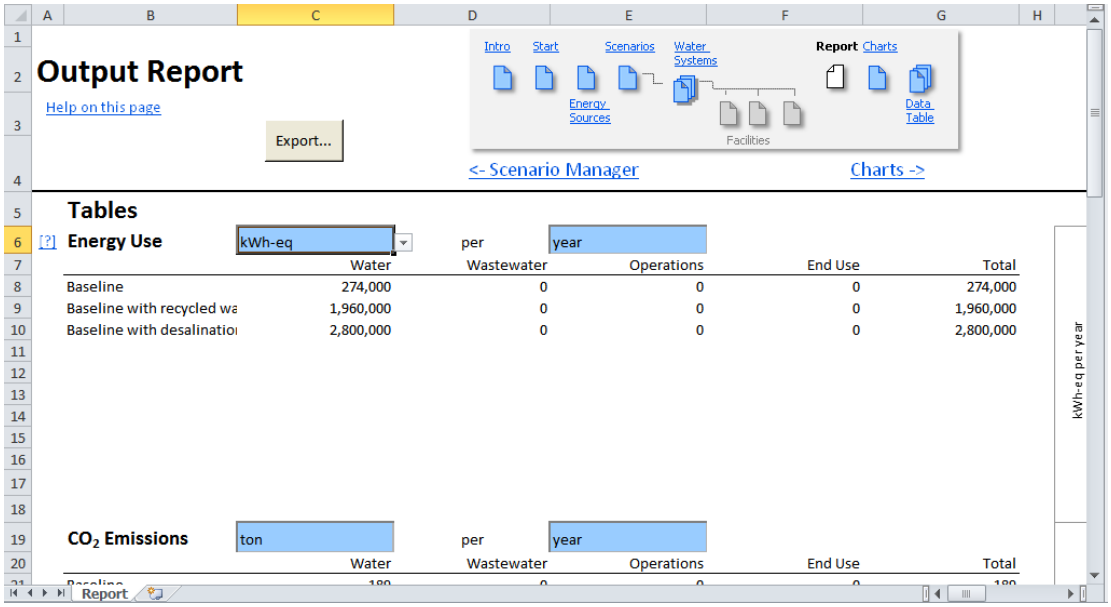


Figure 6.1. Model output page.

For each scenario, WESim reports greenhouse gas emissions for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Each of these greenhouse gases has a different warming potential. To facilitate comparison among scenarios, greenhouse gas emissions are reported in carbon dioxide equivalents ($CO_{2\text{-eq}}$).

Chapter 7

Conclusions

Water managers face increasing challenges and increasing constraints on providing reliable, high-quality water supplies. Rapid population growth, emerging contaminants, rising costs, and climate changes are only some of the challenges. New tools are needed that provide water managers and decision makers with useful information and can facilitate quantification of alternative scenarios for decision support.

The Water–Energy Simulator (WESim) is an easy-to-use analytical tool that allows the user to evaluate the energy and greenhouse gas implications of water management decisions. The tool is suitable for individual water utilities, groups of water utilities, and policymakers and decision makers. The model has been designed to allow the user to input actual operating data for water and energy use, as this will allow an analysis that better reflects operating conditions. Defaults for the energy requirements of various components of the water and wastewater system have also been provided.

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