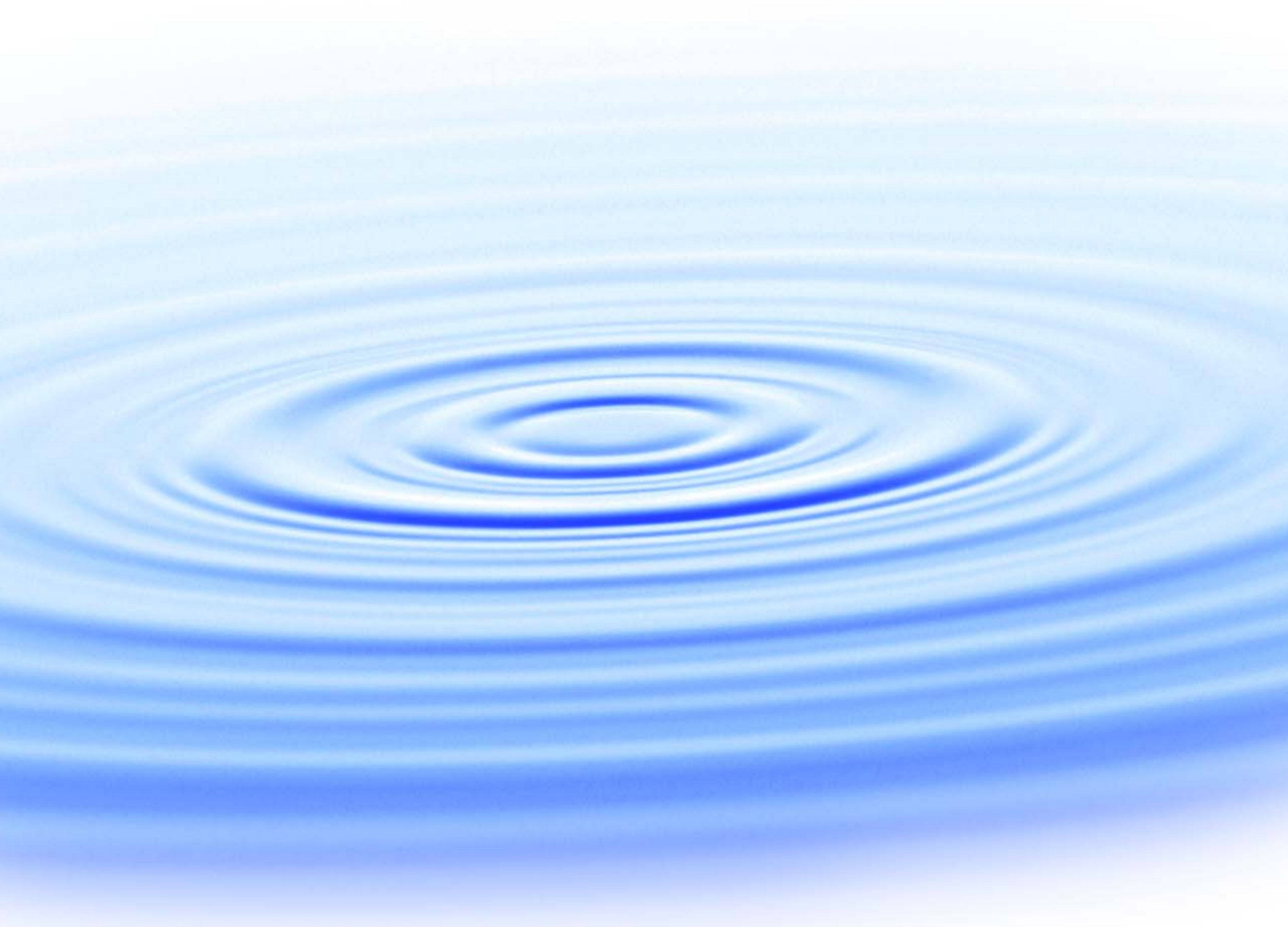
# Implications of Future Water Supply Sources for Energy Demands



WateReuse Research Foundation

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## About the WateReuse Research Foundation

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

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# Contents

List of Figures ........ vii
List of Tables ........ viii
List of Acronyms ........ ix
Foreword ........ xi
Acknowledgments ........ xii
Executive Summary ........ xiii

**Chapter 1. Introduction ........ 1**
1.1 Background ........ 1
1.2 Project Objectives ........ 2

**Chapter 2. Literature Review ........ 5**

**Chapter 3. Model Overview ........ 9**
3.1 Analytical Approach ........ 9
3.2 Model Structure ........ 11
3.3 Energy Use and Greenhouse Gas Emission Calculations ........ 13
3.3.1 Determining Total Energy Use ........ 13
3.3.2 Greenhouse Gas Emission Factors ........ 15
3.3.3 Determining Greenhouse Gas Emissions ........ 17

**Chapter 4. Model Defaults ........ 19**
4.1 Water Source Extraction ........ 20
4.2 Water Conveyance ........ 21
4.2.1 Potable Water Conveyance ........ 21
4.2.2 Recycled Water Conveyance ........ 23
4.3 Water Treatment ........ 23
4.3.1 Chlorine Injection ........ 24
4.3.2 Conventional Treatment for Drinking Water Systems ........ 24
4.3.3 UV and Ozone Disinfection for Drinking Water Systems ........ 26
4.3.4 Low-Pressure Membranes for Drinking Water Treatment ........ 27
4.3.5 Brackish Water Desalination ........ 28
4.3.6 Seawater Desalination ........ 29
4.3.7 Recycled Water Treatment ........ 30
4.4 Water Distribution ........ 32
4.4.1 Potable Water Distribution ........ 33

4.4.2 Recycled Water Distribution ........ 34
4.5 Wastewater Collection ........ 35
4.6 Wastewater Treatment ........ 37
4.7 Wastewater Discharge ........ 39
4.8 Customer End Use ........ 39

**Chapter 5. Case Study ........ 45**
5.1 Santa Clara Valley Water District ........ 45
5.1.1 Introduction ........ 45
5.1.2 Model Inputs ........ 46
5.1.3 Model Outputs ........ 48
5.2 Denver Water ........ 51
5.2.1 Introduction ........ 51
5.2.2 Model Inputs ........ 52
5.2.3 Model Outputs ........ 53

**Chapter 6. Conclusions and Recommendations ........ 57**
6.1 Conclusions ........ 57
6.2 Recommendations ........ 57

**References** ........ 59

# Figures

3.1 Flow diagram of the water and wastewater system ....................................................10
3.2 Example of a simple simulation.................................................................................12

4.1 Energy intensities for conveyance of local and imported water .................................22
4.2 Schematic of a typical drinking water treatment system ............................................25
4.3 Energy intensities for brackish water desalination .....................................................28
4.4 Energy intensity of recycled water treatment .............................................................32
4.5 Energy intensity for water distribution ......................................................................33
4.6 Energy intensity of wastewater collection. .................................................................36

5.1 Map showing location of the Santa Clara Valley Water District service area. ...........46
5.2 Annual energy requirements in 2009 and in 2020 with and without recycled water ....................................................................................................................49
5.3 Annual energy requirements in 2009 and in 2020 for each system component .........50
5.4 Annual greenhouse gas emissions in 2009 and in 2020 with and without recycled water..........................................................................................................51
5.5 Annual energy requirements in 2008 and in Scenarios A, B, and C...........................54
5.6 Annual greenhouse gas emissions in 2008 and in Scenarios A, B, and C ..................55

# Tables


3.1 Heat Content of Common Fuels ........ 14
3.2 Source–Site Ratios by Fuel Type ........ 14
3.3 Greenhouse Gas Emission Factors for Various Primary Fuels and for Electricity .... 16
3.4 Gross Grid Loss Factors ........ 17
3.5 Global Warming Potential Values ........ 18

4.1 Source Extraction Energy Intensity ........ 21
4.2 Energy Intensity for Conveyance of Local and Imported Water ........ 22
4.3 Energy Intensity of Conventional Water Treatment by Treatment Plant Capacity .... 26
4.4 Energy Requirements for Advanced Water Treatment Technologies ........ 27
4.5 Energy Requirements for Brackish Water Desalination by Source Water Salinity ... 29
4.6 Energy Requirements for Seawater Desalination Using Reverse Osmosis ........ 30
4.7 Energy Intensity of Recycled Water Treatment ........ 31
4.8 Energy Intensity for Water Distribution ........ 33
4.9 Energy Intensity of Recycled Water Distribution ........ 35
4.10 Energy Intensity of Wastewater Collection ........ 35
4.11 Energy Intensity for Secondary Treatment by Facility Size ........ 38
4.12 Energy Intensity for Advanced Treatment I by Facility Size ........ 38
4.13 Energy Intensity for Advanced Treatment II by Facility Size ........ 38
4.14 Energy Intensity of Wastewater Discharge ........ 39
4.15 End Use Temperatures for Various Water Uses ........ 40
4.16 Residential End Uses of Water ........ 41
4.17 Commercial End Uses of Water ........ 42
4.18 Industrial End Uses of Water ........ 43

5.1 Energy Intensity for Water System Elements within the Santa Clara Valley Water District ........ 47
5.2 Water Supply Portfolio for the Santa Clara Valley Water District in 2009 and in 2020 with and without Recycled Water ........ 48
5.3 Greenhouse Gas Emission Factors for Electricity Sources Powering the Santa Clara Valley Water District ........ 48
5.4 Energy Requirements for Water Treatment Plants in the Denver Water Service Area ........ 52
5.5 Water Flow Through Each Water Treatment Plant in 2008 and in Three Alternative Scenarios ........ 53
5.6 Total Electricity, Natural Gas, and Diesel Consumption in 2008 and in Scenarios A, B, and C ........ 56

# 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

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 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:

- Burton, Franklin L. *Water and Wastewater Industries: Characteristics and Energy Management Opportunities*; Report CR-106941; Burton Engineering, prepared for Electric Power Research Institute: Los Altos, CA, 1996.
- Wilkinson, R. *Methodology for Analysis of the Energy Intensity of California's Water Systems, and an Assessment of Multiple Potential Benefits through Integrated Water Energy Efficiency Measures*; 2000.
- Electric Power Research Institute (EPRI). *Water and Sustainability: U.S. Electricity Consumption for Water Supply & Treatment—The Next Half Century*; EPRI: Palo Alto, CA, 2002.
- Sauer, P. and Kimber, A. *Energy Consumption and Costs to Treat Water and Wastewater in Iowa. Part 1: An Overview of Energy Consumption and Treatment Costs in Iowa*; Iowa Association of Municipal Utilities: Ankeny, IA, 2002.
- Elliott, T.; Zeier, B.; Xagoraraki, I.; Harrington, G. W. *Energy Use at Wisconsin's Drinking Water Facilities*; ECW Report Number 222-1; Energy Center of Wisconsin: Madison, WI, 2003.
- Wolff, G. W.; Cohen, R.; Nelson, B. *Energy down the Drain: The Hidden Costs of California's Water Supply*; Pacific Institute: Oakland, CA, 2004.
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- ECONorthwest. *Embedded Energy in Water Pilot Programs Impact Evaluation. Prepared for the California Public Utilities Commission*; Draft Report, 2011.

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.

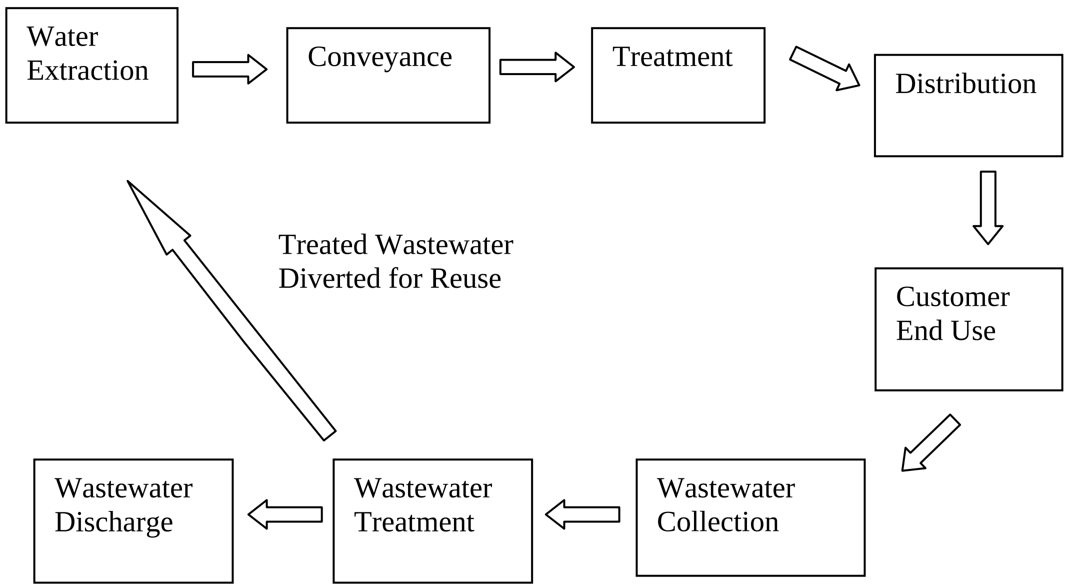


**Figure 3.1. Flow diagram of the water and wastewater system.**

*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<br>Local surface water | Source extraction<br>**Local surface water**<br>*Recycled water* |
| | Water conveyance<br>Raw water pumps | Water conveyance<br>**Raw water pumps** |
| | Water treatment<br>Treatment plant | Water treatment<br>**Treatment plant**<br>*Recycled water treatment* |
| | Water distribution<br>Booster stations | Water distribution<br>**Booster stations**<br>*Recycled water booster stations* |
| | Wastewater conveyance<br>Sewer booster stations | Wastewater conveyance<br>Sewer booster stations |
| | Wastewater treatment<br>Wastewater plant | Wastewater treatment<br>Wastewater plant |
| | Wastewater discharge<br>Gravity-fed | Wastewater discharge<br>**Gravity-fed** |
| | End use<br>Commercial<br>Industrial<br>Residential | End use<br>Commercial<br>Industrial<br>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**

| | | Emissions Factors (kg/energy unit) | | |
|---|---|---|---|---|
| **Fuel Type** | **Energy Unit** | **Carbon Dioxide ($CO_2$)** | **Methane ($CH_4$)** | **Nitrous Oxide ($N_2O$)** |
| Electricity (avg. U.S. grid) | kWh | 0.588 | $1.14 \times 10^{-5}$ | $8.93 \times 10^{-6}$ |
| Electricity (avg. Canadian grid) | kWh | 0.206 | $9.00 \times 10^{-6}$ | $4.00 \times 10^{-6}$ |
| Solar | kWh | 0 | 0 | 0 |
| On-site cogeneration | $ft^3$ or $m^3$ | 0 | 0 | 0 |
| Gasoline | gal | 8.780 | $1.40 \times 10^{-3}$ | $1.00 \times 10^{-4}$ |
| Gasoline (Canadian metric) | L | 2.289 | $1.2 \times 10^{-4}$ | $1.6 \times 10^{-4}$ |
| Diesel fuel | gal | 10.21 | $1.50 \times 10^{-3}$ | $1.00 \times 10^{-4}$ |
| Diesel fuel (Canadian metric) | L | 2.663 | $1.33 \times 10^{-4}$ | $4.00 \times 10^{-4}$ |
| Natural gas (U.S.) | therm | 5.302 | $1.00 \times 10^{-4}$ | $1.00 \times 10^{-5}$ |
| Natural gas (Canadian metric) | $m^3$ | 1.881 | $3.70 \times 10^{-5}$ | $3.5 \times 10^{-5}$ |

*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:

$$E = \frac{\dot{m}gh}{e} \tag{4.1}$$

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 ($5.3 \times 10^{-4}$ 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).

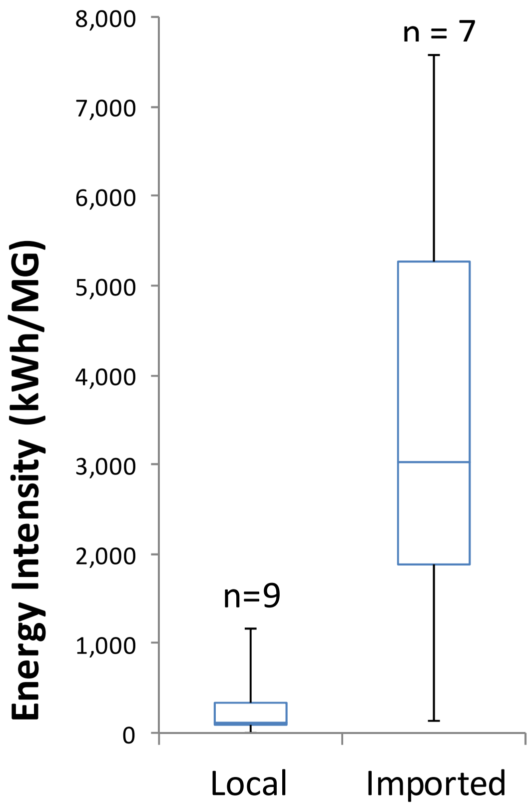


**Figure 4.1. Energy intensities for conveyance of local and imported water.**

*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

$$\begin{aligned} EI = \exp(&10.8346 + 0.6100 \ln(calc\_flow) - 0.0861 \ln(raw\_p\_aflow + 1) \\ &+ 0.1221 \ln(raw\_hp + 1) + 0.7279\, treat\_ox \\ &- 0.7214\, process\_filtr\_direct - 0.8312\, res\_sand - 0.9315\, treat\_iron \\ &+ 0.7946\, process\_oz) \end{aligned} \tag{4.3}$$

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.

.

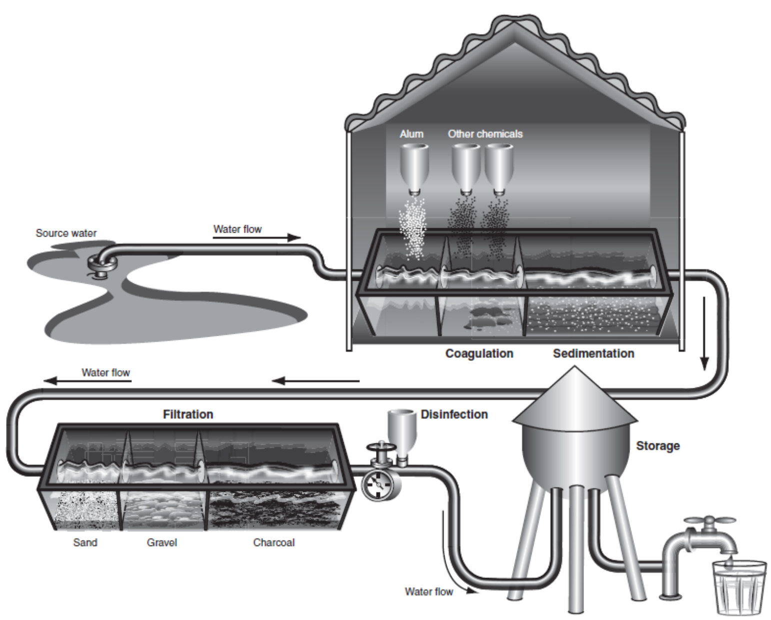


**Figure 4.2. Schematic of a typical drinking water treatment system.**
*Source:* GAO, 2011.

**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).

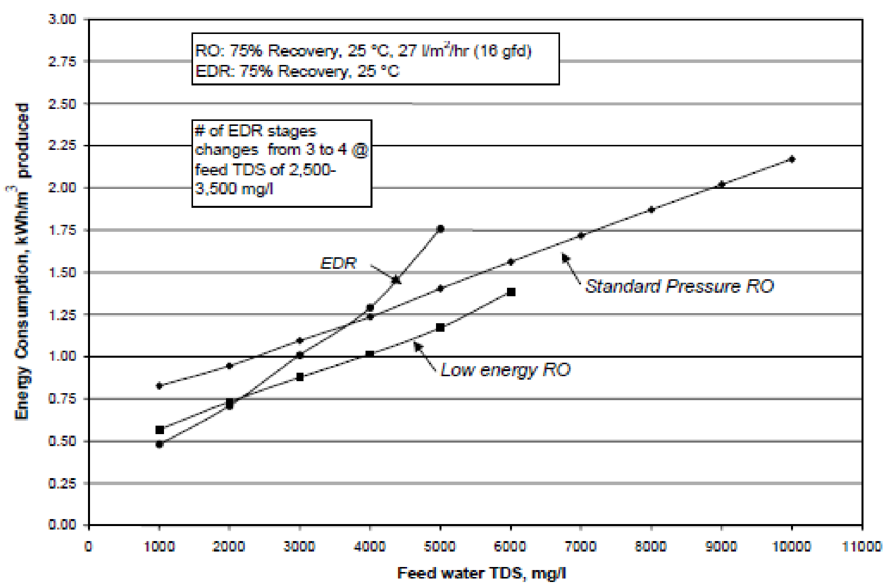


**Figure 4.3. Energy intensities for brackish water desalination.**

*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.

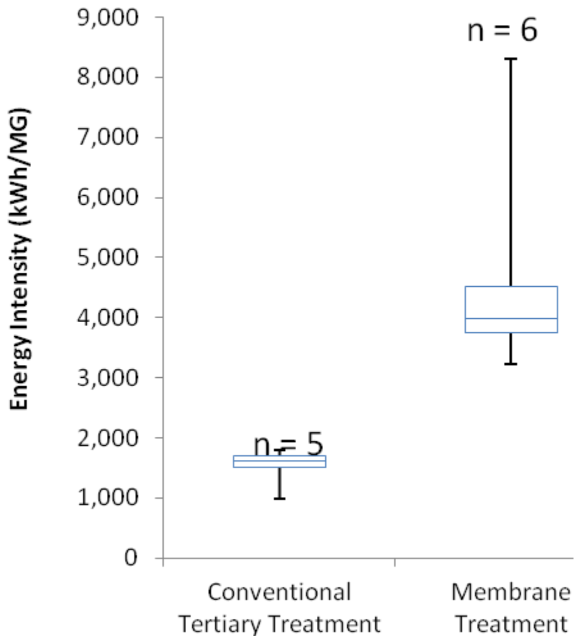


**Figure 4.4. Energy intensity of recycled water treatment.**

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.

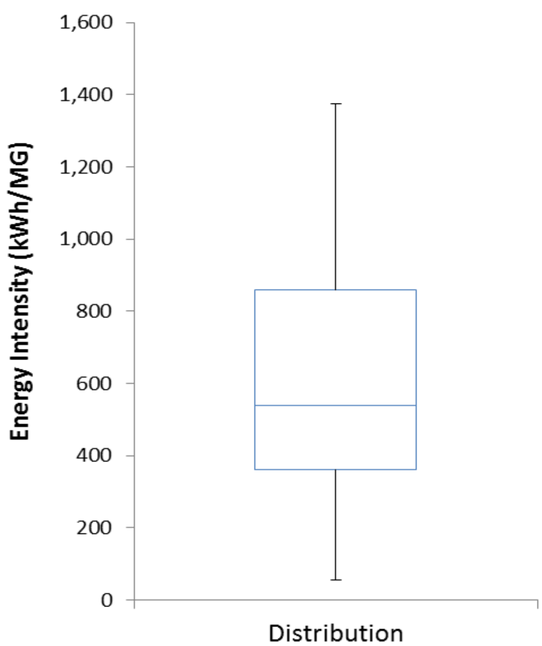


**Figure 4.5. Energy intensity for water distribution.**

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.

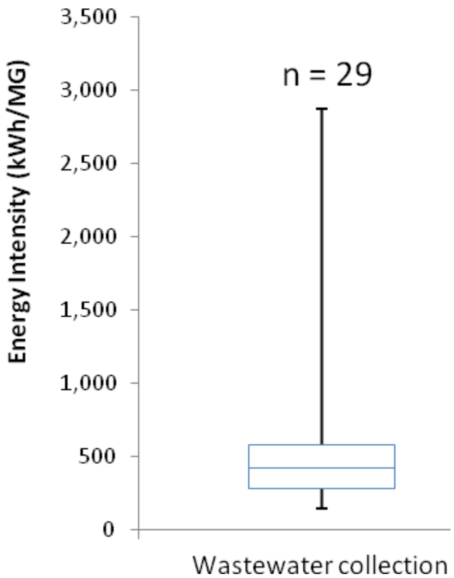


**Figure 4.6. Energy intensity of wastewater collection.**

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* | = | 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 | $1.32 \times 10^{-5}$ | $4.54 \times 10^{-6}$ |
| PWRPA | 0.181 | $3.4 \times 10^{-6}$ | $3.4 \times 10^{-7}$ |

*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.

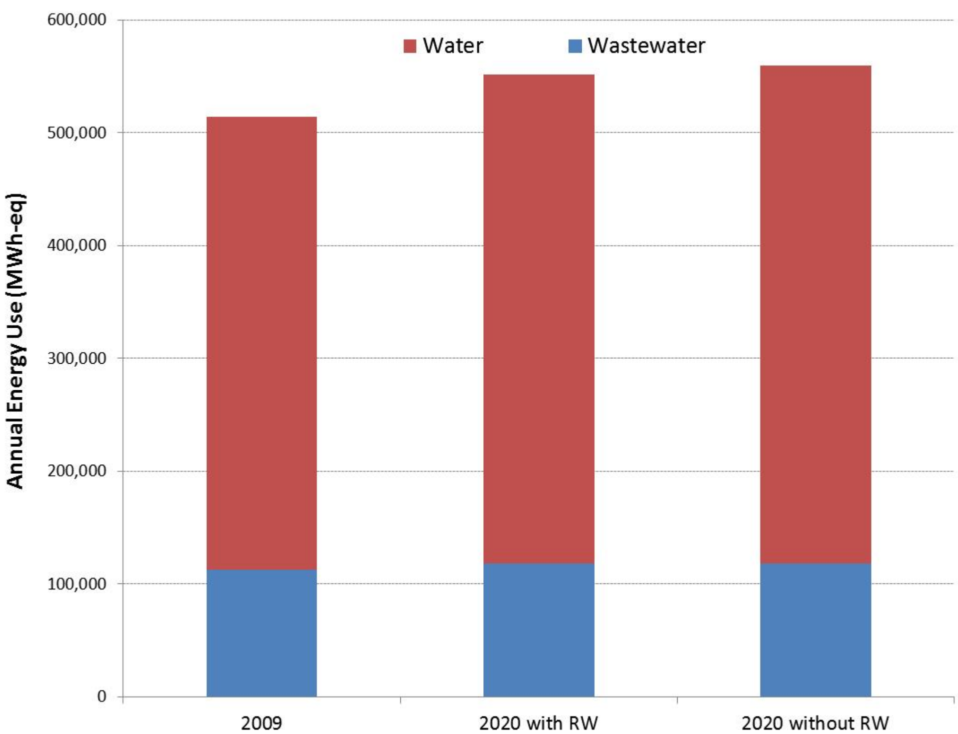


**Figure 5.2. Annual energy requirements in 2009 and in 2020 with and without recycled water in the SCVWD.**

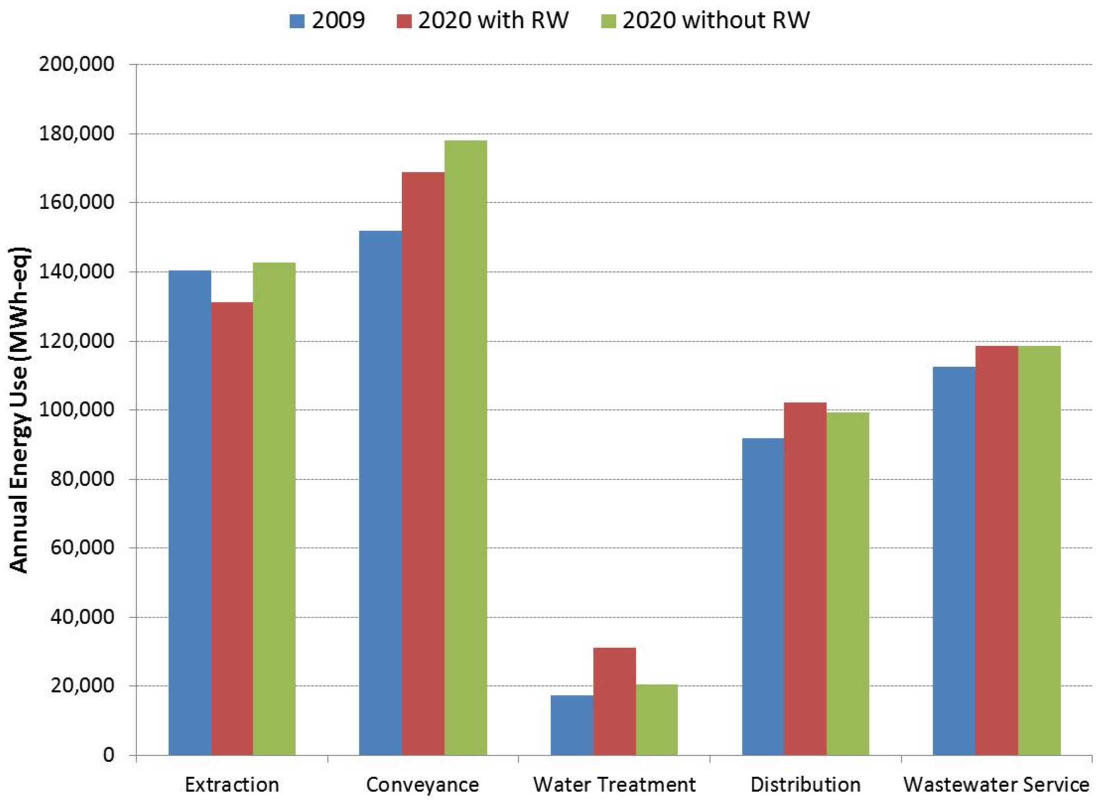


**Figure 5.3. Annual energy requirements in 2009 and 2020 for each system component for the SCVWD.**

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.

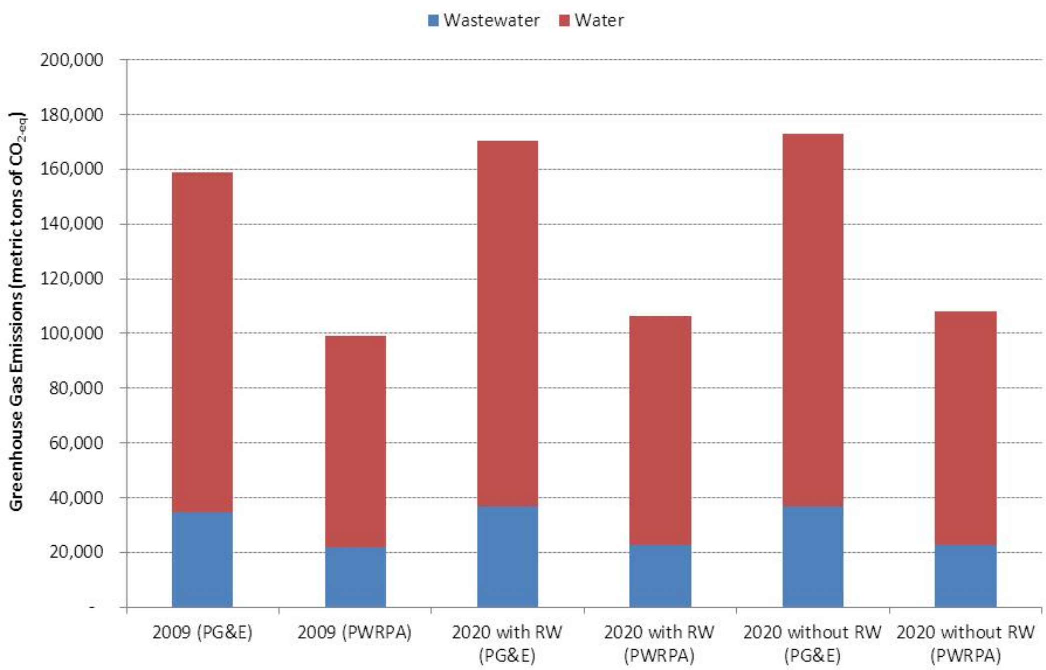


**Figure 5.4. Annual greenhouse gas emissions in 2009 and 2020 with and without recycled water for the SCVWD.**

## 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.

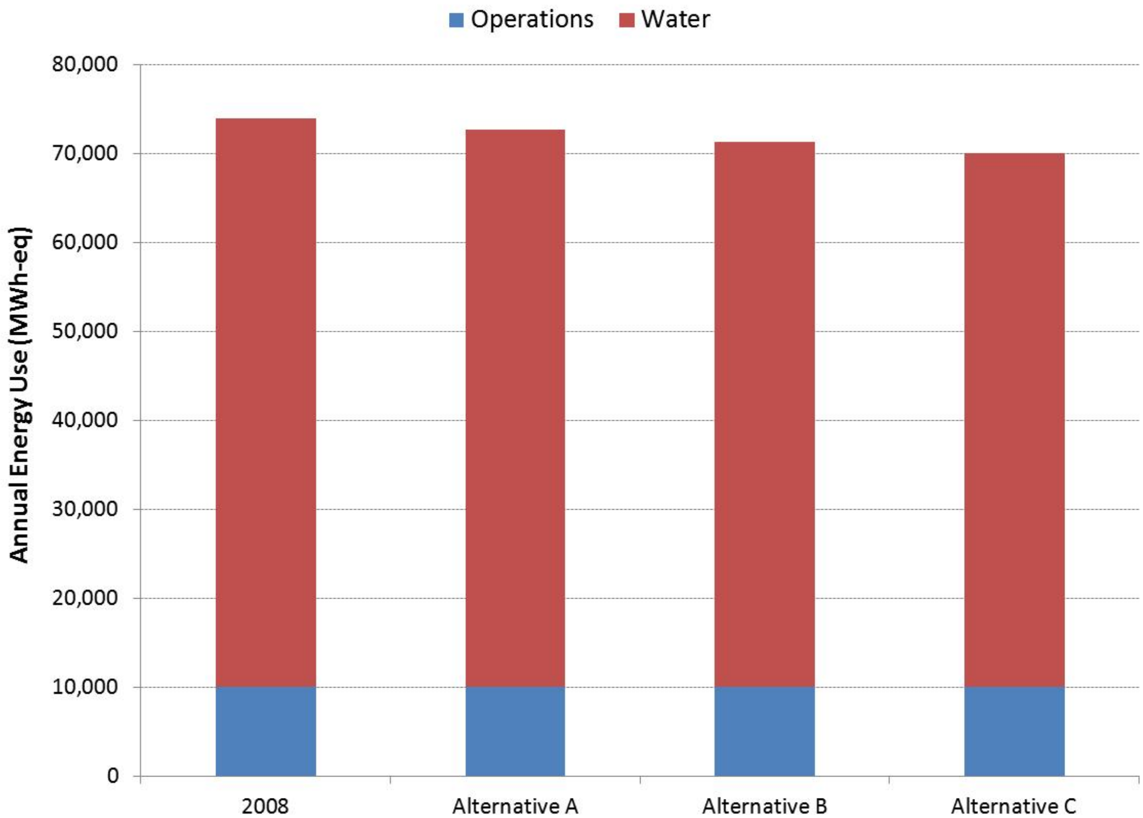


**Figure 5.5. Annual energy requirements in 2008 and in Scenarios A, B, and C.**

*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.

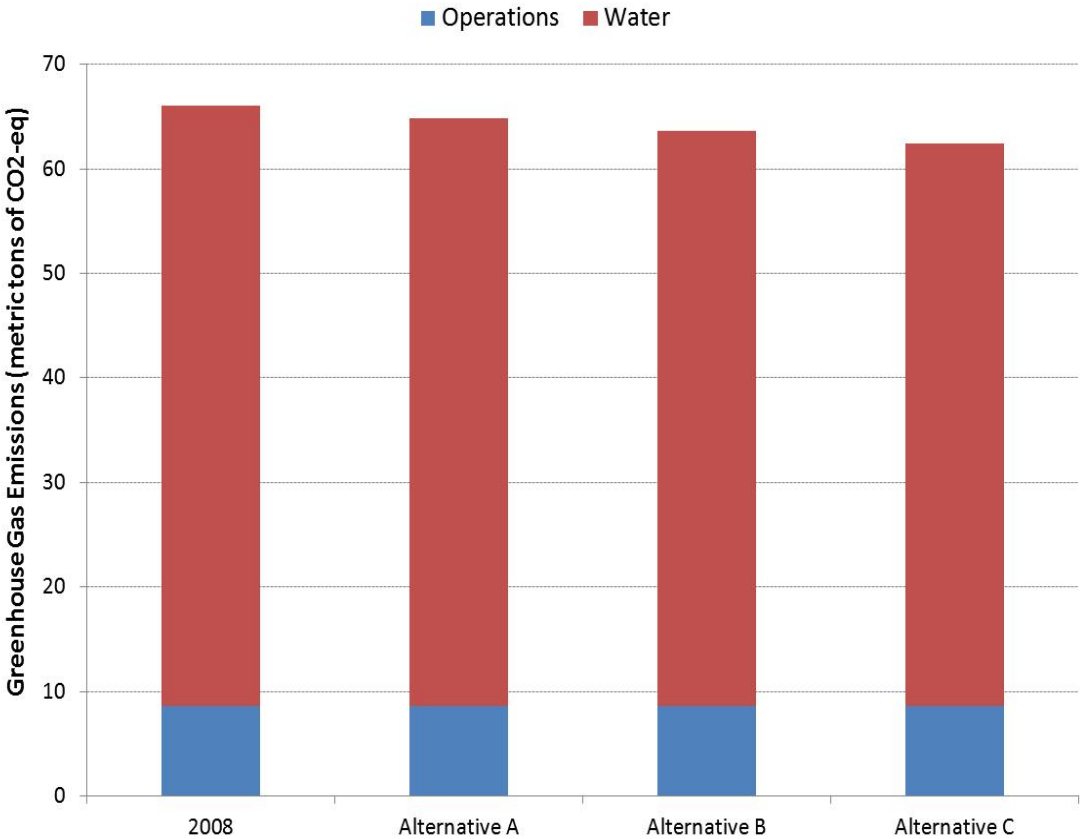


**Figure 5.6. Annual greenhouse gas emissions in 2008 and in Scenarios A, B, and C.**

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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