Arnold Schwarzenegger
Governor

LIFE-CYCLE ENERGY ASSESSMENT OF ALTERNATIVE WATER SUPPLY SYSTEMS IN CALIFORNIA

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
University of California, Berkeley
Department of Civil and Environmental Engineering

July 2005
CEC-500-2005-101

Prepared By:
Arpad Horvath
University of California, Berkeley
Department of Civil and Environmental Engineering
Berkeley, California
Contract No. 500-02-004
Work Authorization 015-007

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Gina Barkalow,
Contract Manager

Kelly Birkinshaw,
Program Area Team Lead

Martha Krebs, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

Acknowledgements

The authors would like to thank all the people at the various agencies contacted to collect case study data for this research, including Marin Municipal Water District (Jared Huffman, Pam Nicolai, and Ron Theisen), Sonoma County Water Agency (Pam Jeane), North Marin Water District (Joe Kauwe), Las Gallinas Valley Sanitary District (Jennifer Joe), City of Oceanside Water Department (Karen Brown, Mike McGrath, Scott Tucker, and others), Metropolitan Water District of Southern California (Brigid Baty and Maureen Burch), and San Diego County Water Authority (Jennifer Nakayama). Also, thanks to David Green of Swinerton for a tour of a water treatment plant construction site.

Please cite this report as follows:

Horvath, A. 2005. *Life-cycle Energy Assessment of Alternative Water Supply Systems in California*. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2005-101.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

What follows is the final report for the PIER-EA Exploratory Grant contract, contract number 500-02-004, work order 015-007, conducted by Arpad Horvath of the University of California, Berkeley. The report is entitled *Life-cycle Energy Assessment of Alternative Water Supply Systems in California.* This project contributes to the Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

Table of Contents

List of Figures

List of Tables

Abstract

In California, traditional water sources for urban use are increasingly insufficient to meet demand. Alternative water sources have higher energy and resource requirements, so the environmental implications should be incorporated into planning decisions, to develop a more environmentally responsible water supply system.

Accounting for energy and environmental effects in water planning requires life-cycle assessment (LCA), a systematic methodology that accounts for energy consumption and environmental emissions caused by extracting raw materials, manufacturing, constructing, operating, maintaining, and decommissioning the water supply infrastructure. In this research, LCA was used to compare three supply alternatives: (1) importing, (2) recycling, and (3) desalinating water. Energy use and environmental emissions were reported for the water supply alternatives, life-cycle phases, and water supply functions. A decision-support tool was developed to evaluate planning decisions with a life-cycle perspective. The tool was used to evaluate the systems of two California water utilities: (1) the Marin Municipal Water District, and (2) the City of Oceanside Water Department.

The results showed that, for both utilities, desalination was the most environmentally detrimental, because that treatment process is energy intensive. The recycled and imported water results were dependent on distance to water source, topography, treatment process, and other issues. For all alternatives, energy consumed by system operation dominated the results. Results can inform future water planning, and the tool can be used to evaluate the environmental implications of water supply decisions.

KEYWORDS: life-cycle assessment, water supply, energy end-use, desalination, recycled water

Executive Summary

Introduction

Currently, water available for urban use is insufficient to meet increasing demand, due to scarce alternative sources, competition between regions, inefficient use, and pollution. A report from the U.S. Department of Interior indicates that a water supply crisis is somewhat or highly likely for many urban coastal areas of California by 2025; and the California Department of Water resources has stated that there will be statewide water shortages by 2020. This research evaluated potential alternative water sources in California, including importing, recycling, and desalinating water, to determine the life-cycle energy and environmental effects of those systems.

A strong connection exists between water provision and energy consumption. According to the California Energy Commission, one-third of electricity in California is used by industry, agriculture, and water and wastewater utilities. In the United States, approximately 3% of national electricity consumption was consumed for water and wastewater services. The energy requirements are expected to grow by 33% in the next 20 years. As readily available water sources are depleted, future supply options will likely have higher energy requirements. The environmental effects of electricity production should be considered in water supply decisions.

In addition, the U.S. water supply infrastructure is aging. The U.S. Environmental Protection Agency estimated that hundreds of billions of dollars will be spent nationwide to provide drinking water between 2000 and 2019. The energy and materials consumed and the construction activities needed to install this infrastructure will increase the life-cycle environmental effects of these systems.

Properly planning for the water supply choices while considering the energy and emissions implications requires life-cycle assessment (LCA) of water supply systems facing these choices. LCA helps target energy reduction efforts, identify air emission sources, and assist in water supply planning.

Purpose

The purpose of this study was to develop standard methods and tools to evaluate and quantify the economic, energy, and environmental impacts of alternative water delivery systems for California, and to apply those methods and tools on two case studies, to promote more sustainable water supply planning decisions.

Project Objectives

This project's objective was to conduct an LCA of two municipal water districts, specifically focusing on the economic implications, energy requirements, and air emissions attributable to the energy consumption required for importing, recycling, and desalinating water in California. To ensure that the LCA results represented a comprehensive analysis, researchers conducted the following tasks:

1. Compared economic implications, energy requirements, and air emissions attributable to energy consumption for importing, recycling, and desalinating water, including the energy implications of material consumption and its supply chain.
2. Evaluated the environmental effects, including relative energy consumption and related air emissions, of the different phases of the water supply system (supply, treatment, and distribution), life-cycle phases (construction, operation, maintenance), and specified activities (material production, material delivery, equipment use, and energy production).
3. Evaluated the economic, environmental, and energy implications of separate distribution systems for potable and non-potable water.
4. Conducted a sensitivity analysis to determine parameters and processes in the water supply system that contribute most to energy use and related environmental emissions.

Project Outcomes

To conduct the LCA for two case studies, the authors created a model that quantifies material and energy inputs into water systems, as well as the environmental outputs from those systems. The model has been developed into a computer-based decision-support tool—the Water-Energy Sustainability Tool (WEST)—that assesses the environmental effects of water systems for water utilities considering or currently using these water alternatives. WEST can be used by individual utilities, statewide planners, and policy makers to evaluate the environmental effects of their water supply decisions and incorporate those into the planning process. This analysis also included the energy implications of material consumption and its supply chain, but decommissioning was not included, because of a lack of information.

Using WEST, researchers determined the economic, energy, and air emission effects for the water supplied by two case studies—the Marin Municipal Water District (MMWD), and the City of Oceanside Water Department (OWD). In doing so, they addressed the tasks listed above.

Conclusions

Based on this study, researchers reached the following conclusions:

Imported Water

- The effects of imported water are highly site-specific, depending greatly on the amount of pumping necessary to transport the water from the source to the treatment facility. In the case study systems, most environmental effects occur in the supply phase.
- Treatment of imported water is not a significant contributor to energy demand and resulting emissions for either case study, especially for the MMWD, which uses a simpler treatment process.

- For imported water, the effects of construction and maintenance are smaller for the OWD case study, due to economies of scale: the supply system provides water to the entire region and the effects are widely distributed.

Desalinated Water

- The desalination system air emission factors are the largest for all analyzed substances as well as for energy use, on account of the reverse osmosis (RO) systems in place in the case study utilities.
- Treatment is the largest contributor to the desalination emissions in both MMWD and OWD, because of the energy intensity of RO systems.
- Most of the environmental effects from desalination are due to electricity production, but material production is also important.
- Seawater desalination creates more environmental burden than desalinating brackish groundwater, primarily due to the higher level of energy consumption required.
- The maintenance phase most affects the desalination systems, because the treatment process (e.g., RO membranes, cartridge filters) includes more components that must be replaced regularly.

Recycled Water

- Distribution was the largest global warming potential contributor to both of the recycled water systems studied. The water treatment plants are located near the wastewater treatment plants that supply their water, minimizing the supply phase impacts.
- Treatment was not a significant contributor to environmental effects. Both systems have relatively simple treatment processes (i.e., filtration and disinfection at the MMWD and filtration only at the OWD).
- Because wastewater treatment plants tend to be located at lower elevations, to minimize the energy necessary to collect sewage, distributing recycled water to customers tends to require significant pumping.
- Environmental emissions caused by recycled water system construction and maintenance in the OWD case study are smaller than for the MMWD system. The OWD recycling system is simpler and requires fewer routine inputs.
- The emissions per 100 acre-feet of water production and per length of pipeline for the recycled water distribution systems are higher than for the imported and recycled water distribution systems, due to the scale of the systems. Recycled water systems are typically at least an order of magnitude smaller than potable water systems in terms of both water produced and geographic scale. As a result, when environmental emissions are reported in terms of these parameters, recycled water results are higher.
- Due to the low emissions from the supply and treatment systems, recycled water remains an environmentally competitive and preferable source of water over desalinated water and, in some cases, imported water.

WEST

- The WEST, in its current form, has certain limitations. It does not assess all environmental emissions, account for ecological effects, or quantify environmental impacts such as human toxicity. In addition, it does not allow for analyses of alternative infrastructure choices or energy mixes.
- Generally, utilities and water planners are not aware that it is possible to assess the environmental effects of their systems using LCA; as a result, the analysis is not included in decision-making.

General

- For the MMWD case study, a significant portion of the water supplied to the utility comes from rainfall via reservoirs. Only the considered sources (imported, desalinated, and recycled water) were included in the analysis.
- Two case studies do not provide enough data to obtain complete and detailed understanding of the environmental effects of water supply systems. More case studies are needed for better understanding.
- The case study water costs indicate that desalination is consistently more expensive than importing water. In the MMWD system, recycled water is the most expensive water source; recycled water costs were not available for the OWD system.
- Potable water distribution emission factors varied significantly between the two case studies, because the OWD distribution system is designed to distribute water by gravity, whereas the MMWD must rely on significant pumping.
- For all case studies and alternatives, the operation life-cycle phase uses the most energy and creates the most emissions. The maintenance phase is also important. Construction effects are considerably less significant.
- In all case studies and alternatives, the energy produced for use in water systems creates the most air emissions for all the considered activities. Material production is also a significant contributor. Material delivery and equipment use are negligible in all cases.
- Both parameters of the sensitivity analyses had significant effects on the results. For the change in material service life, the effects were in the construction and maintenance phase. For the energy mix, the effects were primarily in the operation phase.
- The selection of an energy mix can greatly influence the results, according to the sensitivity analysis. The WEST tool should also be improved to allow the comparison of customized energy mixes.
- The results are affected by data quality. Two factors contributed to the difficulties in data collection and potentially to data quality issues: (1) security concerns that prevented full disclosure, and (2) lack of data collection by utilities. Security concerns primarily affected the detail of information about supply and distribution systems. Lack of data collection by utilities was a more significant limitation. For example, in some cases electricity

consumption data were available only on a systemwide basis. Assumptions were made to allocate energy use by the systems' components.

- Results for similar California water systems considering the same alternatives may be different. The outcome will be affected by site-specific issues such as topography, process design, location, distance to water sources, climate, scale, and other factors.

Recommendations

The following recommendations can be made based on this research:

Imported Water

- Based on energy considerations, in the case study systems, water importation should be encouraged if supply pumping can be minimized. However, for imported water systems, the environmental effects of withdrawing water from the ecosystem are not captured by the current WEST model. These effects may be significant and should be included in the decision process along with the WEST results.

Desalinated Water

- If desalination is to be pursued in earnest as a water supply alternative in California, efforts should be made to advance desalination technologies so the process is more energy-efficient and the materials are longer lasting.
- Given current process requirements, projects that desalinate brackish groundwater should be encouraged above those that desalinate seawater. However, if seawater intrusion is occurring, pumping water will exacerbate the problem and should not be encouraged.

Recycled Water

- The results of this analysis indicate that the needs of water end-users in California should be evaluated in the planning process. Water should not always be treated to the potable water standard when a lower-grade product can meet the consumer's needed.
- Standards for most non-potable applications requires little treatment (and therefore energy use) beyond what is required for discharge from the wastewater treatment plant. Recycled water should be encouraged in areas where it can be provided at a reasonable cost and where consumers for non-potable water exist. However, efforts should be made to minimize distribution system pumping.
- The increasing popularity of indirect reuse (e.g., when recycled water is used to recharge aquifers which are used for potable supply) in California ensures that applications for recycled water exist within most utility service areas.
- Future analyses should evaluate the effects of putting separate piping systems in new construction, so that recycled water can be used for toilet-flushing, landscaping, and similar uses. Such information would help attract and prioritize potential recycled water customers.

WEST

- This assessment of the environmental effects of water systems should be improved and extended in the future to include assessment of other emissions (e.g., emissions to land and water) and impact assessments (e.g., human or environmental toxicity) and to include alternative infrastructure choices. WEST should be improved in the future to better capture service life variability, to allow the comparison of possible energy mixes, and to assess the environmental effects of water supply which are not due to infrastructure.
- An effort should be made to share the capabilities of WEST with utility directors and other water supply planners, so they can incorporate its results into their future water decisions.
- A simplified form of the tool should be made available so that it can be used to make "back of the envelope" estimates of the environmental burden of water supply alternatives.

General

- Results for similar California water systems considering the same alternatives may be different. The outcome will be affected by site-specific issues including topography, process design, location, distance to water sources, climate, scale, and other factors.
- Similar studies should be conducted for additional utilities to provide further information about the environmental effects of water systems. For instance, additional case studies could evaluate elements of the systems that are affected by siting and scale.
- Future research should emphasize the areas that create the greatest energy and environmental burden (e.g., desalination, system operation, electricity production, material production).
- Efforts should be made to obtain higher-quality, specific data for use in future analyses. Utilities should be encouraged to collect data that can be used for this and similar research.

Benefits to California

Water supply decisions are based on several factors, including economic, political, and reliability concerns. Heretofore, the comprehensive and systemwide life-cycle environmental effects of the water infrastructure have not been a factor in these decisions. The conceptual model and associated decision-support tool developed in this research will allow utilities and other planners to incorporate these effects and externalities into their decision processes, and with more informed analyses, strive for sustainable solutions. The methodology developed for this research, and the knowledge gained from it, can be applied to other aspects of water and wastewater systems, to further reduce future energy use and environmental emissions in California.

This research provides groundwork for future research on the use of energy by water and wastewater systems by identifying the processes that are most energy and pollution intensive in the entire water supply life-cycle. California will benefit from this research and from the development of WEST through a better understanding of water systems, and by encouraging the sustainability of the infrastructure and the systems designed to provide water.

1. Introduction

1.1 Background and Overview

In California, the water available for urban use is insufficient to meet increasing demand due to scarce alternative sources, competition between regions, inefficient use, and pollution. A report from the U.S. Department of Interior indicates that a water supply crisis is somewhat or highly likely for many urban coastal areas of California by 2025 (USDOI 2003); and the California Department of Water resources has stated that there will be statewide water shortages by 2020. (DWR 1998). The state is expected to experience a shortage of four to six million acre-feet (AF) by 2010 without changes. To prevent a shortage, urban water systems in California are evaluating new water sources as required by California's Urban Water Management Plan (UWMP) Act (California Assembly 1990). Every five years, urban water utilities (e.g., those serving more than 3,000 customers) are required to prepare and submit documents outlining expected water demand and supply sources for the next 20 years. The next UWMPs are due in 2005, so decisions about future water sources are currently being made. Other state legislation ensures that water planning is a continuous, ongoing process (CDWR 2003).

This research evaluated potential alternative water sources in California, including importation, wastewater reclamation (also known as water recycling), and desalination. These sources are defined as follows:

- **Imported water** is water transported from outside the water retailer's service area and, generally, is purchased from a water wholesaler agency.
- **Desalinated water** uses saline water as a potable water source after a reverse osmosis (RO) treatment process.
- **Recycled water** systems reuse effluent from wastewater treatment plants after it is treated to higher standards appropriate for non-potable use.

Each of the three alternatives consumes different amounts of energy in different phases of the life-cycle. Because the supply systems vary in terms of the size of infrastructure, complexity of the treatment process, and amount of maintenance required, understanding the life-cycle energy implications is important.

A strong connection exists between water provision and energy consumption. According to the California Energy Commission, one-third of electricity in California is used by industry, agriculture, and water and wastewater utilities. The Energy Commission recommends energy-efficient improvements for water-related utilities. However, the Energy Commission recommendations focus on facility operation and do not address bigger-picture life-cycle and planning issues involved in supplying water

Worldwide, 2%–3% of energy consumption is used to pump and treat urban water (ASE 2002). In the United States, approximately 75 billion megawatt-hours—3% of national electricity consumption—was consumed for water and wastewater services. Globally, the total energy demand is expected to grow by 33% in the next 20 years. As readily available water sources are depleted, future supply options will likely have higher energy requirements. The environmental effects of electricity production should be considered in water supply decisions.

In addition, resource consumption and construction processes will increase energy consumption and the negative environmental burden. One German study estimated that water, sewer, and district heating pipelines (as well as other infrastructure) account for 10%–20% of the total urban building mass; the value varies inversely with building density (Herz 2002). Because the infrastructure in this country is aging, the U.S. Environmental Protection Agency (EPA) has estimated that nationwide capital spending to provide drinking water would have to be $154–$446 billion between 2000 and 2019 (USEPA 2002). The energy and materials used and the construction processes needed to install this infrastructure will increase the life-cycle environmental effects of these systems.

Properly planning for the water supply choices while considering the energy and emissions implications requires life-cycle assessment (LCA) of water supply systems facing these choices. LCA helps target energy reduction efforts and assist in water supply planning. To promote more sustainable water supply planning decisions, the authors created a model which quantifies material and energy inputs into water systems and environmental outputs. The model has been developed into a computer-based decision-support tool, the Water-Energy Sustainability Tool (WEST), which assesses environmental effects of water utilities considering or currently using these water alternatives. The tool can be used by individual utilities, statewide planners, and policy-makers to evaluate the environmental effects of their water supply decisions and incorporate those into the planning process (Stokes 2004). The methodology developed for this research and the knowledge gained it can be applied to other aspects of water and wastewater systems to further reduce future energy use and environmental emissions in California.

Water supply system sustainability is increasingly a concern. In Silicon Valley, several industries and the Santa Clara Valley Water District are joining forces to reduce greenhouse gas (GHG) emissions by 20% below the 1990 level by 2010 (Rogers 2004). A recent article in *Environmental Science and Technology* emphasized the value of sustainable water supply provided by recycled water (Levine 2004). In addition, several LCAs of water and wastewater systems have been conducted abroad. Their results are informative; however, they do not necessarily apply to U.S. systems, particularly in regards to disinfection practices and sludge handling. None of the studies provide results directly relevant to the water situation in California. Table 1 outlines the findings of relevant studies. Each study is described briefly in the following paragraphs.

Table 1. Current and Prior Research Summary

	Current Research	Van Tilburg 1997	Crettaz 1999	Friedrich 2002	Herz 2002	Lundie 2004	Hermanowicz 2001	Das 2002
Water System	**X**	X	X	X	X	X		X
Water recycling and dual distribution systems	**X**	X				X	X	
All treatment processes	**X**	X	X			X		
U.S. focus	**X**						X	X
Infrastructure production	**X**	X		X	X	X		
Construction processes	**X**				X			
Infrastructure operation	**X**	X	X	X	X	X	X	X
Alternate water sources	**X**					X		
Energy analysis	**X**	X	X	X		X	X	
Environmental analysis	**X**	X	X	X		X		X
Environmental valuation	**X**							
Systemwide supply chain effects	**X**							

- An LCA studied Sydney, Australia's base case plan for providing water and sewer services in the year 2021 (Lundie 2004). The study also evaluated changes in demand management, electricity sources, efficiency improvements, alternative water sources (including recycled and desalinated water), and the effects of localized water and wastewater provision for new development. Systemwide supply chain effects and construction processes were not included. The study determined that permanent construction materials did not contribute significantly to environmental effects, but that use of routine inputs (e.g., chemicals and electricity) are important. The study found water recycling to be environmentally beneficial; however, desalination was not, because other sources were much less energy intensive.

- Herz and Lipkow conducted an environmental assessment of the life-cycle of water mains and sewers in Germany, including concrete, ductile iron (DI), and polyethylene (PE) pipe for water mains (Herz 2002). The study considered production, construction, operation, maintenance, and recycling. It ignored external effects of construction, such as traffic disruption. The research considered traditional pipe installation and no-dig (trenchless) pipe installation. Impacts were measured in terms of carbon dioxide (CO_2) emissions. Water mains were assumed to be laid 2.5 ft. deep. Service lives of the pipes varied. DI pipe was assumed to last 100 years; PE pipe, 70 years. No-dig installation reduced CO_2 emissions by 20%–30%. The CO_2 emissions for DI and PE were comparable, while for concrete pipe, emissions were roughly twice as high.

- A study by van Tilburg et al. (1997) compared using 100% drinking water from surface water (requiring complex treatment) with using 50% potable treated surface water and 50% untreated surface water, as well as potable groundwater (requiring simple treatment) for all uses with using 50% potable and 50% water recycled from wastewater treatment effluent. The study included construction of a dual piping system. They found that water recycling was not environmentally beneficial when the potable source required only simple treatment. These results, however, are not applicable in California, where alternate water sources are scarce.

- Crettaz et al. (1999) determined that using low-flush toilets reduces energy and water use compared to traditional toilets, but found collecting rainwater for toilet-flushing unfavorable in terms of energy. According to Crettaz et al., the energy consumption for Swiss drinking water supply breaks down as follows: water treatment plant (44%), supply water (38%), activated carbon and ozone (10%).

- Friedrich studied two water treatment processes for plants in South Africa to determine the relative environmental effects of conventional treatment and membrane filtration (Friedrich 2002). The study included both the construction and decommissioning, or end-of-life, life-cycle phases. Decommissioning may involve leaving components in place at the end of their service life or demolishing or deconstructing facilities. Ultimately, system components may be recycled, landfilled, or incinerated. The operation phase, particularly coal-powered electricity generation, dominated the environmental effects. The most energy-intensive components were ozonation and sludge disposal. He evaluated global warming potential (GWP), ozone depletion potential, acidification, eutrophication, photo-oxidant formation, aquatic ecotoxicity, terrestrial ecotoxicity, and human toxicity. For the most environmentally destructive case, operation accounted for 81%–98% of the effects, depending on the impact considered. Decommissioning accounted for less than 1% of the effects for all impacts. Life-cycle energy use was higher for membrane filtration than for conventional treatment. The results for other environmental impacts were mixed.

- Hermanowicz et al. (Hermanowicz 2001) described an energy analysis of a water recycling plant in the San Francisco Bay Area and calculated the energy used to distribute water for internal plant use and to external customers. The analysis, however, included only system operation, not construction or decommissioning. The study found that recycled water distribution consumed almost twice as much energy as treatment.

- Das (2002) conducted an LCA of chlorine and ultraviolet irradiation (UV) disinfection processes in wastewater treatment. This analysis focused on chemical releases to water resources and the biological impacts on them when treated water is discharged, rather than on energy-related effects. It did not consider the effects of construction of the alternative treatment systems. Das concluded that UV disinfection is environmentally preferable to chlorination because it reduces chemical residuals in the receiving waters and improves safety by eliminating chlorine releases

The studies described above informed the research described herein. However, no study has been conducted which provides an LCA for alternative water sources available in California.

1.2 Project Objectives

The more energy that is needed to supply water to Californians, the more air emissions and greenhouse gases the state will produce. From an environmental and energy use perspective, the best sources of water for a California city may vary, depending on the local conditions. A better understanding of the environmental effects of water systems is necessary. To better foster this understanding, this project's objective was to conduct an LCA of two municipal water districts.

To ensure that the LCA results represented a comprehensive analysis, researchers conducted the following tasks:

1. Compared economic implications, energy requirements, and air emissions attributable to energy consumption for importing, recycling, and desalinating water—including the energy implications of material consumption and its supply chain.
2. Evaluated the environmental effects, including relative energy consumption and related air emissions, of the different phases of the water supply system (supply, treatment, and distribution), life-cycle phases (construction, operation, maintenance), and specified activities (material production, material delivery, equipment use, and energy production).
3. Evaluated the economic, environmental, and energy implications of separate distribution systems for potable and non-potable water.
4. Conducted a sensitivity analysis to determine parameters and processes in the water supply system that contribute most to energy use and related environmental emissions.

1.3 Report Organization

Section 2 outlines the life-cycle assessment methodology used for the analysis and the tasks completed as a part of the analyses. Section 3 discusses the outcomes of the research. Section 4 presents the conclusions and recommendations based on the results of the study, and outlines the benefits of this research to California. The appendices provide additional detail on the data, assumptions, spreadsheet workings, project information, and the case studies.

2. Project Approach

2.1 Research Method

This section outlines the research method used for this study. The following includes a general description of LCA, a discussion of the application of LCA to water systems, a brief introduction to the WEST model, and information about the specific case studies.

2.1.1 Life-cycle Assessment

The framework of this study was to conduct a LCA of the water supply system for two communities. LCA is a systematic, quantitative approach to evaluating the impacts of a product or process from "cradle to grave" (Graedel 2003; Curran 1996). LCA considers all energy and environmental implications of processes through the entire life-cycle, including design, planning, material extraction and production, manufacturing or construction, use, maintenance, and end-of-life fate of the product (reuse, recycling, incineration, or landfilling). This type of analysis was first described over a decade ago by the Society for Environmental Toxicology and Chemistry (SETAC) (SETAC 1991; SETAC 1993) and refined by the EPA in 1993 (USEPA 1993). The procedure was formalized by the International Organization of Standardization (ISO) 14040 series standards (ISO 1997; ISO 1998; ISO 2004). Figure 1 presents the LCA framework (USEPA 1993). Process-based LCA requires data collection from various companies, government agencies, and published studies to evaluate the inputs and outputs to the system.

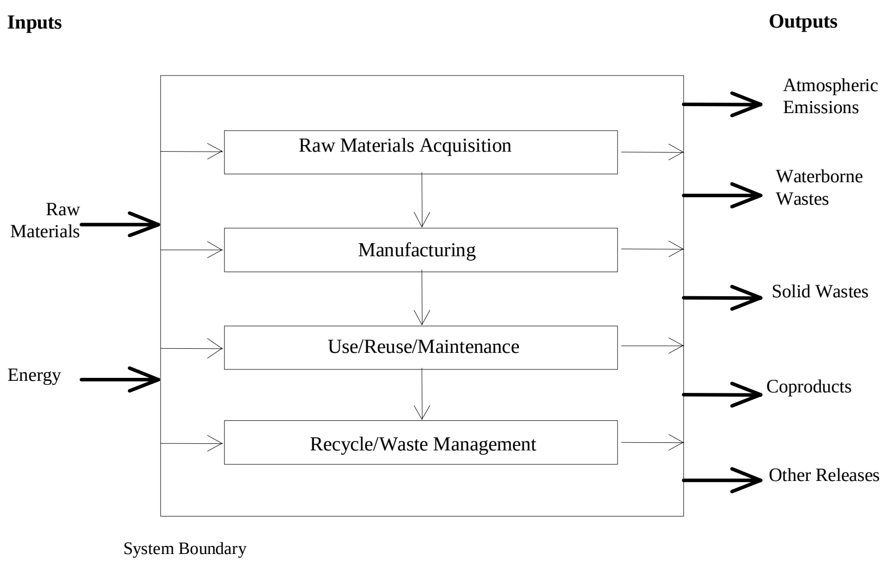


Figure 1. LCA inventory analysis framework

Source: Vigon 1993

Economic Input-Output Analysis-based LCA (EIO-LCA) is an alternative matrix-based LCA approach. It uses the U.S. Department of Commerce's economic input-output model and augments it with publicly available resource consumption and environmental emissions data (CMU 2004; Hendrickson 1998). As a general interdependency model, the economic input-output model describes interactions between 485 sectors of the economy. For an expenditure in a given economic sector, the model estimates how much is spent directly in that sector, as well as in the supply chain. In addition, the model calculates environmental emissions associated with the specified expenditure. EIO-LCA is comprehensive, considering all resource inputs and environmental emissions, and provides information on direct emissions associated with the studied process and indirect emissions occurring in the supply chain. The PI has been one of developers of the EIO-LCA model since 1995.

Recently, a form of hybrid LCA has been developed which leverages the strengths of each approach while minimizing the disadvantages associated with them. For instance, EIO-LCA can only be used to estimate emissions due to manufacturing a product but cannot be used to assess the operation phase. To estimate vehicle tailpipe emissions, for example, it is necessary to use process-based LCA. Alternatively, it is time-consuming and expensive to obtain estimates of material production energy use through the supply chain using process-based LCA.

2.1.2 The Water-Energy Sustainability Tool

In order to quantify air emissions and energy use associated with water systems, the WEST was created using a hybrid LCA approach. This tool employs user-defined input data to evaluate emissions and energy use throughout the life-cycle of the system, including construction, operation, and maintenance. Decommissioning of the system is not included because sufficient data were not available and it is expected to contribute negligibly to the final result. (One study found that decommissioning contributed less than 1% of the overall environmental burden [Friedrich 2002].)

The tool evaluates energy and material use for four categories of activities: material production, material delivery, equipment use, and energy production. Material production assessment allows the user to inventory the materials used in the system and evaluate the energy and environmental effects of their manufacture or provision throughout the supply chain using EIO-LCA. For example, energy used to produce materials and operate equipment needed to construct infrastructure (transport and distribution pipeline and treatment plants), produce and deliver chemicals and equipment for the treatment process, and to operate and maintain the plant was included in the system boundary. Materials considered may include reinforced concrete, pipe, pumps, valves, electrical and control systems, and chemical storage equipment. Table 2 describes more fully the components of the water system and supply chain included in the study. Figure 2 shows a process flow diagram for the water supply system.

The material delivery component assesses the emissions produced and energy used to transport materials to the end-use location by truck, train, ship, or airplane. Equipment use assesses the emissions and fuel use from operating non-transport equipment—especially construction equipment and maintenance vehicles. Both material delivery and equipment use were analyzed using a process-based approach. Energy production focuses on the impact of producing electricity or fuel (e.g., diesel, gasoline, or jet fuel needed for vehicle operation) used in the system. Electricity generation was assessed using process-based LCA and fuel production was assessed using EIO-LCA.

Table 2. LCA System Boundaries

Construction	Operation	Maintenance
-Fuel use and emissions for construction equipment and delivery vehicles; and - Energy use and emissions for production of construction materials, treatment equipment, and electricity used in initial installation, including the supply chain.	-Energy and emissions for operating transport, treatment, and distribution phases; - Fuel use and emissions for transporting and disposing of sludge; - Fuel use and emissions from delivery and operational vehicles; and - Energy use and emissions for producing chemicals and other routinely used materials (including supply chain).	-Energy use and emissions used to produce replacement parts (including supply chain); - Fuel use and emissions from maintenance and delivery vehicles.

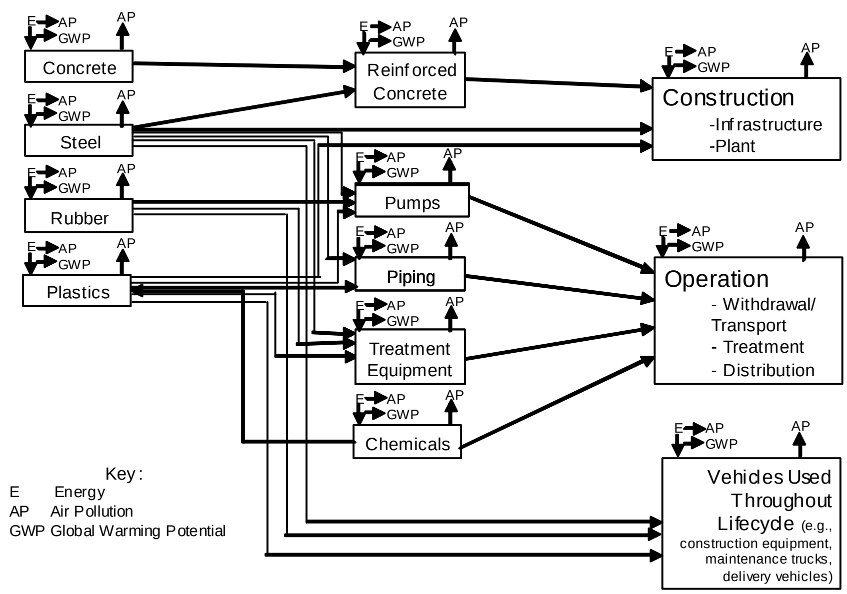


Figure 2. Example water supply system process flow diagram

Each item entered in the tool must be further categorized by the user according to the associated life-cycle phase. An item may be used in the construction, operation, or maintenance phase of the system. These are defined as follows:

- *Construction* includes the facility construction and production, delivery, and installation of equipment present at start-up for the entire system, as well as construction equipment operation.
- *Operation* includes all chemicals, non-capital materials (i.e., cartridge and bag filters), and energy used by the system continuously.
- *Maintenance* includes replacement parts for capital equipment (e.g., piping, pumps, membranes, and filter media) and cleaning chemicals for the system.

In addition, each item should be defined as a component of water supply (transporting water from the source to the treatment plant), treatment (ensuring water meets regulatory water quality standards), or distribution (storing water and transporting it to the end-user after treatment). Figure B.1 provides an illustration of the three different phases of the system.

The WEST tool created is useful for several audiences, including planners, designers, construction contractors, plant operators, utility administrators, and policy analysts. It can be used to evaluate the effects of a variety of water supply decisions, including:

- selecting alternative water supplies (e.g., recycled, imported, or desalinated);
- designing system expansions (e.g., centralized versus distributed treatment);
- changing drinking water standards (i.e., in-plant or point-of-use arsenic removal if a stricter standard is adopted);
- evaluating alternative treatment processes (e.g., membrane versus dual-media filtration, chlorine versus ultraviolet disinfection); and
- choosing materials for infrastructure improvements (e.g., steel versus concrete reservoir, plastic versus iron, steel, or concrete pipe).

Finally, the tool can be used to identify areas where energy efficiency improvements can be focused, material use can be reduced, and environmental burden can be minimized.

2.1.2.1 WEST Worksheet Descriptions

The WEST tool is an Excel-based spreadsheet and contains worksheets in four categories: (1) data entry, (2) data, (3) calculations, and (4) results. Appendix B provides additional tool documentation.

2.1.2.1.1 Data Entry Worksheets

The data entry pages allow the user to input data related to the analyzed system. A general information page requires the user to define the name and location of the water system being analyzed, the demographics of the analyzed system, the major facilities (e.g., treatment plants, reservoirs, and large pumping stations), and model parameters (e.g., analysis time-frame and functional unit). The general information worksheet also allows the user to divide the components of the system into unique "Facilities" with different parameters such as the volume of water processed (e.g., volume of water transported in a particular aqueduct or volume treated at a particular treatment plant). Figure B.2 shows the general data entry worksheet. The facilities table can be seen at the bottom of Figure B.2.

On a separate worksheet, the user also enters data related to construction, transportation, and maintenance equipment used in the system. This page allows the user to define the size, model year, engine capacity, productivity, fuel type, and fuel use of various pieces of construction, transportation, or maintenance equipment. For instance, the user can select the excavator model used for construction and the type of dump truck used for sludge disposal during operation. The worksheet contains a variety of predefined equipment characteristics, but the user can define more precise information if desired. In addition, the user can enter custom equipment parameters. Figure B.3 shows a portion of the equipment input worksheet. Additional information about these data entry worksheets is available in Appendix B.3.1.1.

A separate data entry page is available for each of the four included activities—material production, material delivery, equipment use, and energy production. The activity entry worksheets are discussed further in Appendix B.3.1.2. An overview of the structure of the tool—as well as the data which the user must provide—is listed in Figure 3.

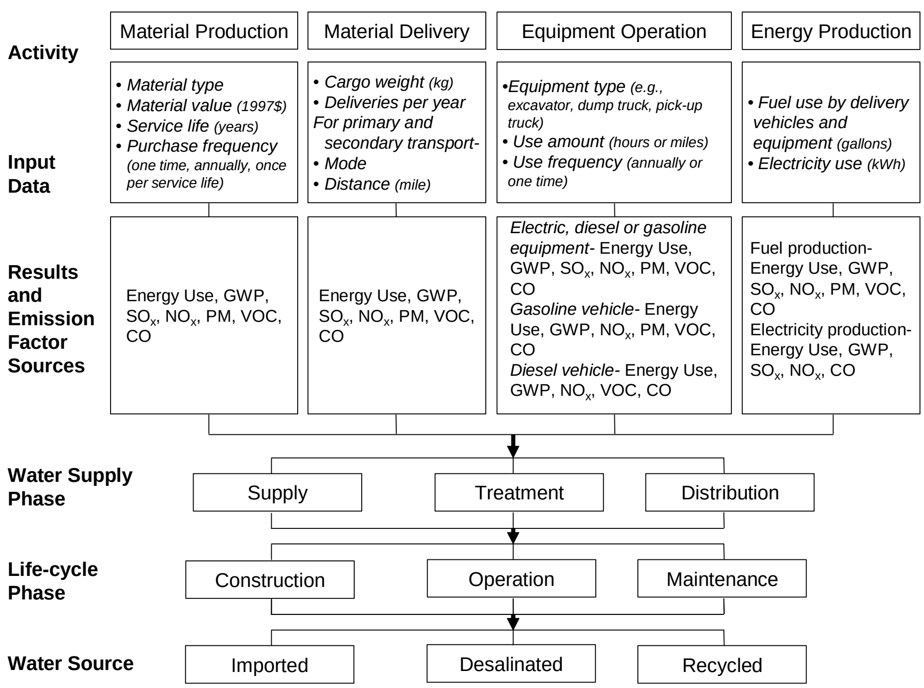


Figure 3. WEST structure

2.1.2.1.2 Calculation Worksheets

Calculation pages combine user-entered information and standard data to determine energy use and air emissions for all categories.

The material production effects are estimated using emission factors obtained from the EIO-LCA model (CMU 2004). Each material available in the tool's drop-down menu is associated with an economic sector included in EIO-LCA. Table B.1 provides a representative list of common components of a water system and their associated EIO-LCA sectors. The default service life for each material type is also listed. Emission factors for each of the EIO-LCA sectors are included in Appendix D.1.1. Additional information, including the equation used to determine the environmental effects associated with material production, is included in Appendix B.3.2.1.

Material delivery emissions are a function of delivery distance and frequency, cargo mass, and mode of transportation. Material delivery by truck, rail, ship, and airplane can be evaluated by the WEST tool. Transport vehicle emission factors are from (OECD 1997; Romano 1999; Sorenson 1995; EEA 2002; ATA 2001; IPCC 1999) and are included in Appendix D.1.3. Appendix B.3.2.2 provides additional detail.

Equipment use emissions are a function of model year, equipment type, motor capacity, and amount of use. Sources for emissions factors are provided in the following references: diesel road vehicles (USEPA 1995), diesel non-road vehicles and equipment (CARB 2002; USEPA 1998), gasoline vehicles and equipment (USEPA 1996), and electric equipment (E-GRID 2002) are provided. The emission factors are included in Appendix D.1.4. The general equation used to calculate emissions is provided in Appendix B.3.2.3 (Equation B.3). Equipment data is from a variety of sources (e.g., Caterpillar 1996; John Deere 2004) and is included in Appendix D.2.

Energy production includes emissions due to refining fuel for use in delivery vehicles and construction equipment and caused by electricity generation. Fuel production emissions are evaluated using emission factors from EIO-LCA (CMU 2004). The environmental effect is calculated as shown in Appendix B.3.2.4, specifically in Equation B.1. Electricity generation emission factors were obtained from EPA's E-GRID model (E-GRID 2002) and are included in Appendix D.1.5. The emission factors are specific to the energy mix for California and are available for any U.S. state.

2.1.2.1.3 Results Worksheets

Results from the cumulative calculations are displayed both numerically and graphically on the results pages. Results are broken down to display information according to water source (imported, desalinated, and recycled water), life-cycle phase (construction, operation, and maintenance), water supply phase (supply, treatment, and distribution), and activity category (material production, material delivery, equipment use, and energy production). Energy use, GWP, and air emissions (nitrogen oxides [NO_x], particulate matter [PM], sulfur oxides [SO_x], volatile organic compounds [VOC], and carbon monoxide [CO]) are reported in terms of average annual emissions per functional unit of output. Figure 4 presents a sample results page, which is intended to show how results are presented in the WEST tool rather than to provide meaningful results. Results may also be reported in terms of external costs and material use, as described in Appendix B.3.3.1 and B.3.3.2, respectively.

2.1.2.2 *Material and Equipment Use Estimation*

A separate Excel-based spreadsheet was created which compiles and evaluates the materials and equipment needed to construct the common components of a water system prior to entry in the WEST model. This data analysis companion tool is described in Appendix B.4. Data used for material consumption and equipment use estimation is provided in Appendices D.3, D.4, and D.5.

2.1.3 Water Utility Case Studies

Two public water utilities, one in Northern California and one in Southern California, were evaluated for the case studies. The following criteria were applied for selecting utilities for the case study: the utility had to be an urban water system that imports a significant portion of its water supply, has recycled water programs, and either desalinates water or plans to do so. If a desalination system was not currently in place, a system design had to exist. Once candidate utilities that met these criteria were identified, the final case studies were selected based on data quality and availability.

Results Explanation:
In the table at right, and the first row of graphs, the results are broken down by three different criteria (life-cycle phase, water supply phase, and water source). The table below and bottom two rows of graphs show the results broken down specifically into the 27 possible categories. Refer to the key to abbreviations at right to decode the category code.

Contaminant	Life-cycle Phase			Water Supply Phase			Water Source		
	C	O	M	S	T	Di	I	D	R
Energy	#####	#####	#####	8.E+02	4.E+03	2.E+03	#####	#####	#####
CO_2 eq.	#####	#####	#####	7.E+01	3.E+02	1.E+02	#####	#####	#####
NO_x	9.E-02	3.E-01	5.E-01	7.E-02	6.E-01	2.E-01	1.E-01	6.E-01	1.E-01
PM	2.E-02	1.E-02	1.E-01	2.E-03	9.E-02	4.E-02	2.E-02	9.E-02	2.E-02
SO_x	9.E-02	1.E-01	6.E-01	3.E-02	5.E-01	2.E-01	1.E-01	6.E-01	8.E-02
VOC	3.E-02	2.E-02	3.E-01	2.E-03	3.E-01	4.E-02	2.E-02	3.E-01	2.E-02
CO	1.E-01	3.E-01	4.E-01	7.E-02	4.E-01	3.E-01	2.E-01	5.E-01	1.E-01

* VOC category sums VOC, NMVOC, and HC results from other pages for simplicity.

Key to Abbreviations

Life-cycle Phase		Water Supply Phase		Water Source	
C	Construction	S	Supply	I	Imported
O	Operation	T	Treatment	D	Desalinated
M	Maintenance	Di	Distribution	R	Recycled
Contaminants				**Units**	
CO_2 eq.	Carbon dioxide equivalents	NMVOC	Non-methane volatile organic compounds	Mg	Million grams
NO_x	Nitrogen oxides	VOC	Volatile organic compounds	GJ	Gigajoules
PM	Particulate matter	CO	Carbon monoxide		
SO_x	Sulfur oxides	HC	Hydrocarbons		

Emissions (Mg, except energy in GJ))

Contaminant	Construction									Operation									Maintenance								
	Supply			Treatment			Distribution			Supply			Treatment			Distribution			Supply			Treatment			Distribution		
	I	D	R	I	D	R	I	D	R	I	D	R	I	D	R	I	D	R	I	D	R	I	D	R	I	D	R
Energy	#####	#####	#####	8.E-01	#####	#####	#####	#####	5.E+01	4.E+02	2.E+02	#####	#####	#####	#####	6.E+01	#####	#####	#####	#####	3.E+00	3.E-01	1.E+03	#####	#####	#####	#####
CO_2 eq.	4.E-01	7.E-01	1.E-01	6.E-02	#####	#####	#####	#####	3.E+00	3.E+01	1.E+01	#####	8.E-01	#####	#####	5.E+00	#####	#####	2.E-01	6.E-01	2.E-01	2.E-02	9.E+01	#####	#####	#####	#####
NO_x	2.E-03	3.E-03	4.E-04	5.E-04	2.E-02	9.E-03	2.E-02	2.E-02	2.E-02	3.E-02	1.E-02	1.E-02	3.E-03	2.E-01	2.E-02	5.E-03	1.E-02	5.E-02	7.E-04	3.E-03	7.E-04	9.E-05	3.E-01	3.E-02	5.E-02	5.E-02	7.E-03
PM	3.E-04	6.E-04	8.E-05	7.E-05	4.E-03	2.E-03	4.E-03	5.E-03	3.E-03				5.E-04	1.E-02	2.E-03				2.E-04	5.E-04	1.E-04	2.E-05	6.E-02	1.E-02	1.E-02	1.E-02	1.E-03
SO_x	1.E-03	3.E-03	4.E-04	2.E-04	2.E-02	5.E-03	2.E-02	2.E-02	1.E-02	9.E-03	4.E-03	4.E-03	2.E-03	7.E-02	1.E-02	1.E-03	3.E-03	1.E-02	8.E-04	2.E-03	8.E-04	9.E-05	4.E-01	2.E-02	6.E-02	7.E-02	7.E-03
VOC	4.E-04	7.E-04	1.E-04	1.E-04	1.E-02	2.E-03	5.E-03	5.E-03	4.E-03				1.E-03	1.E-02	5.E-03				2.E-04	7.E-04	2.E-04	2.E-05	2.E-01	4.E-03	1.E-02	1.E-02	2.E-03
CO	2.E-03	4.E-03	7.E-04	3.E-04	1.E-02	7.E-03	3.E-02	3.E-02	2.E-02	3.E-02	1.E-02	1.E-02	2.E-03	2.E-01	2.E-02	4.E-03	1.E-02	4.E-02	1.E-03	4.E-03	1.E-03	1.E-04	2.E-01	2.E-02	9.E-02	1.E-01	1.E-02

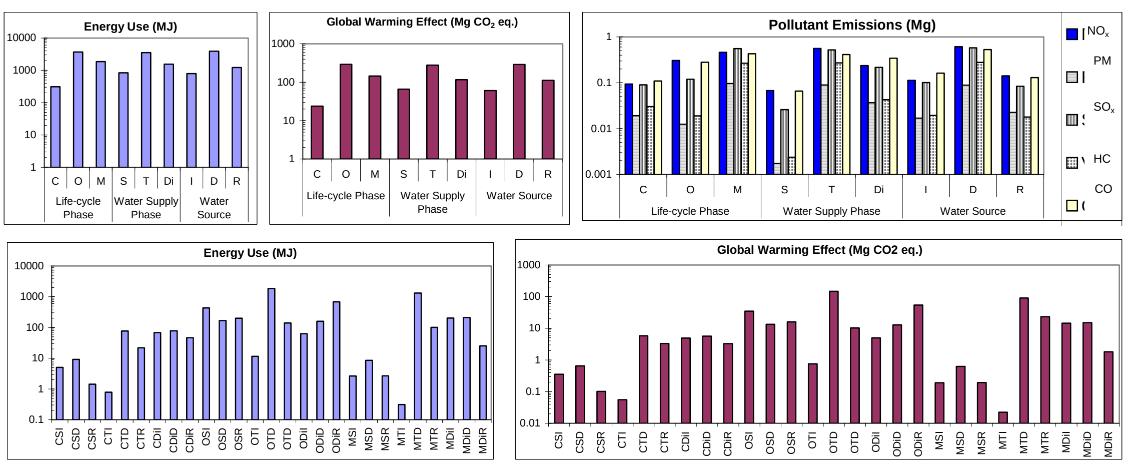


Figure 4. Sample results worksheet

The selected utilities were the Marin Municipal Water District [MMWD] located in Marin County in the San Francisco Bay Area, and the Oceanside Water Department [OWD] in northern

San Diego County. Both serve a population of approximately 200,000 people, and provide a total of approximately 30,000 AF of water each year. However, the climate differs between the two areas. Marin County receives 30 inches of rainfall annually, whereas, Oceanside receives only 10 inches.

Information about the infrastructure used by these utilities and water wholesalers associated with them was compiled. The information used in the analyses was obtained from a combination of published information from each utility, site visits, and published industry information. Assumptions about necessary infrastructure and material consumption were made based on industry practice and engineering judgment when other data were unavailable. A brief description of the necessary assumptions, the two case study utilities, and case study data quality follows. The economic cost of each water source is provided in Table 3.

Table 3. Economic, energy, and environmental results

Economic, Energy, and Environmental Results (Reported per 100 AF)						
	Import		Desalinate		Recycle	
	MMWD	OWD	MMWD	OWD	MMWD	OWD
Average Economic Costs ($)	125,000	24,000	150,000	50,000	190,000	NA
Energy Use (GJ)	789	942	3883	1972	1217	851
GWP (Mg)	60	75	290	145	112	67
SO_x (Mg)	0.1	0.1	1	0.3	0.1	0.04
NO_x (Mg)	0.1	0.1	1	0.3	0.1	0.1
PM (Mg)	0.02	0.01	0.1	0.04	0.02	0.01
VOC (Mg)	0.02	0.01	0.3	0.1	0.02	0.01
CO (Mg)	0.2	0.1	1	0.2	0.1	0.1

NA = Not available.

2.1.3.1 Case Study Assumptions

In both case studies, some imported water infrastructure is used to provide water to other utilities. In these cases, emissions due to construction and maintenance are allocated to the case study utilities based on their average annual water provision through the shared infrastructure. In addition, the following assumptions were used to inventory the case studies:

For water system buildings:

- Unless more specific information was available, reinforced concrete buildings were assumed to have a 2-foot (ft.) thick foundation and 1-ft. thick walls. Reinforced concrete is assumed to contain 2% steel by volume.
- Pump station size was assumed to be a function of the pipe size and the number of pumps housed within the facility. Pumping facility size is assumed to be a function of pipe size and number of pumps. For transmission pipe larger than 30-inch (in.) diameter, pump stations are assumed to have an area of 500 square feet (ft^2) per pump. When pipe size is between 14 in. and 30 in., the facility is assumed to be 200 ft^2 per pump. Small diameter pipe requires 100 ft^2 per pump. Each pumping facility includes one pressure regulating valve.

- Electrical and control system components at all facilities, as well as piping and landscaping at treatment plants, were not specifically inventoried. Electrical and control equipment are assumed to be valued at 3% and 9% of equipment costs in the given system, respectively (Peters 2003). Piping within treatment plants (e.g., chemical delivery systems) and landscaping were similarly estimated as 17% and 2.5% of equipment costs, based on the same source. Piping within treatment systems was assumed to be composed of 20% bronze valves, 35% DI pipe, and 45% polyvinyl chloride (PVC) pipe.

For water pipelines:

- A limited number of pipe sizes (diameters [in.] :1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 24, 30, 36, 40, 60, and 75) were included in the tool for simplicity. For pipe diameters smaller than 75 in. which are not included in the tool, lengths were distributed proportionally to the closest diameters smaller and larger. For example, if the utility has 50 feet of 33-in. diameter pipe, the final calculations included 25 feet of 30-in. pipe and 25 feet of 36-in. pipe. For pipes with diameters larger than 72 in., data for 72 in. pipe were used. Pipes were consolidated into five common materials: (1) asbestos cement (AC), (2) concrete, (3) DI, (4) PVC, and (5) steel. All plastic pipes were classified as PVC; metal pipe was allocated to either DI or steel, based on similar material and/or price. AC pipe, commonly used in water distribution systems, was banned in 1997 but still comprises a significant component of water distribution systems. As a result, no prices are available for this commodity. AC pipe was assumed to be equivalent to non-reinforced concrete pipe in both cost and size. Pipe size and cost information is included in Appendix D.3. Cement-mortar lined pipe is assumed to include the mortar thicknesses listed in Appendix Table C.1 (Mays 2000).

- Fittings (e.g., bends, wyes, tees, reducers) were assumed to be located on average every 0.25 miles for large-diameter pipe (14-in. or larger) and every 0.1 miles of smaller diameter pipe. For estimating purposes, all fittings were assumed to be ductile iron 90° bends. Fitting size and cost information is included in Appendix D.3.

- Isolation valves are assumed to be placed every 0.75 miles of pipe if no other valve information is available. Butterfly valves are used for this purpose in large-diameter pipe; gate valves are used in pipe with diameters less than 14 in. Storage tanks are assumed to have a check valve and two altitude valves. Costs were available for butterfly, gate, check, and globe valves (Means 1997, Peters 2003). Globe valves were used to estimate cost for valves other than those listed. Most other valves are created from a globe or similar valve body type (Mays 2000). Valve size and cost information is included in Appendix D.3.

- Isolation and other pipeline valves are assumed to be housed in underground concrete valve boxes. Each box is assumed to house two valves on average. For pipe with diameters larger than 30 in., the valve boxes are assumed to be 100 ft^2 with a depth of 8 ft. or 1 ft. below the pipe bottom, whichever is deeper. If more than one valve is housed in the box, the area is assumed to increase by 25 ft^2 for each additional valve. The boxes are constructed of cast-in-place reinforced concrete. For pipes with a diameter between 14 in. and 30 in., the boxes are assumed to be 50 ft^2, with an additional 10 ft^2 for each additional valve and a depth of 1 ft. below the bottom of the pipe. Small diameter pipes are assumed to be housed in boxes that are 10 ft^2 and 6 in. deeper than the bottom of the pipe. For pipe with diameters of 30 in. and smaller, pre-cast concrete boxes are installed.

For electricity use, when specific data were not available, electricity use was based on the total estimated motor capacity in horsepower (hp) of pumps in the system plus an additional 15% for non-pumping electricity use (e.g., lighting, controls) for phases except potable distribution. Equation C.1 in Appendix C.2.2 shows the equation used to allocate electricity use.

Chemicals used in the case study water treatment processes and their associated properties are listed in Appendix C.2.3.

For construction processes:

- Construction and equipment use effects were assessed based on what it would take to construct the system under modern conditions. The results do not reflect the actual emissions from construction, because much of the infrastructure is several decades old. Technology and emission standards have changed since construction took place.
- Equipment use impacts are included for a cement mix truck, dump truck, loader, excavator, compactor (plate and roller models), crane, concrete pump, and concrete vibrator are incorporated into the assessment. Other equipment will be used during construction, including welding equipment, booms, generators, and air compressors. However, since construction information was scarce, only certain commonly used equipment was incorporated into the assessment. In the future, an attempt to assess the use of other equipment will be made to improve the model.
- Emission factors depend on the equipment model year and, for diesel road equipment, the cumulative number of miles traveled by the truck. The cumulative miles factor accounts for increasing emissions as the equipment ages. All equipment was assumed to be from the 2001 model year; diesel trucks were assumed to have 70,000 cumulative miles.
- Soil compaction was assumed to be done in 6-in. lifts. For all excavation activities (e.g., buried pipelines, valve boxes, and foundations), the area was excavated 1 ft. deeper than required for the facility and the soil beneath the foundation was compacted. It was assumed that soil volume would increase by 125% when excavated and decrease to the original volume when re-compacted.
- Excavations for pipelines were assumed to be 1 ft. deeper and 1 ft. wider than the pipe. Tunnel excavation is assumed to be conducted with a large excavator using productivity rates for rock.
- Reinforced concrete used in construction was assumed to be composed on 2% reinforcing steel by volume. The actual proportion of reinforcing steel depends on the engineering design and will vary. Plywood forms were assumed to be used for cast-in-place concrete. These forms are assumed to be used three times prior to disposal.
- Assumptions about hours of equipment use were based on industry norms (Means 1997) and manufacturer's data for specific models. These values assume that earthwork is done in common soil. Emissions will increase if conditions are more unfavorable. WEST could be improved to account for this in the future.

For material delivery:

- The transportation mode used to deliver system components was determined based on the transport distance. If the transport distance was 50 miles or less, a local truck was assumed to be used. For distances between 50 and 1,000 miles, a long-distance truck was assumed to be used. When the transport distance exceeded 1,000 miles, the equipment was assumed to be transported primarily by rail. When rail was used, it was assumed that secondary transport by local truck was necessary for the final 25 miles.
- One exception to the material delivery assessment is concrete delivery. Because concrete must be delivered in special concrete mixer trucks, the emissions due to concrete delivery are included in equipment use rather than material delivery.
- Material delivery calculations require material mass (in kilograms [kg]). The mass of certain components mass was not available and could not be estimated. This is especially true for materials in highly aggregated categories where the mass of materials included varies widely, including landscaping, electrical equipment, and control equipment. When the mass could not be estimated, the effects of material delivery were excluded. As a result, material delivery emissions are underestimated. However, the effect associated with delivery of these materials is expected to be negligible. In the future, a method for estimating the mass of these materials will be sought.

2.1.3.2 Marin Municipal Water District

The MMWD currently obtains most of its water (72%) from rainfall; this water was not considered in the analysis. The remaining water is from importation (26%) and recycling (2%). The recycled water utilizes wastewater effluent which has been treated for non-potable uses such as irrigation, commercial car washes, and similar purposes. Due to reliability and environmental concerns, the MMWD is considering replacing the imported water source with desalinated water. The reliability issues are outside of the scope of LCA and must be evaluated by MMWD separately from the results of this study. A description of each of the water sources follows. Detailed case study information, including the inventory of water system facilities, material consumption, and are included in Appendix C.3. Economic costs for each alternative are listed in Table 3.

The MMWD system information was obtained from the following sources: (Huffman 2001; Jeane 2004; Kauwe 2004; MBK 2002; MMWD 1990; MMWD 1995; MMWD 2003; MMWD 2004; MUWMP 2003; NMWD 2004; SCWA 2004; Sheikh 2001; Theisen 2004; URS 2003).

2.1.3.2.1 Imported Water

The MMWD's imported water supply (8,100 AF per year) is obtained from deep wells beneath the Russian River, approximately 20 miles away. The water is pumped over hilly terrain to the MMWD service area. The imported water system utilizes pipelines owned and operated by the Sonoma County Water Agency and the North Marin Water District. The supply system consists of almost 200,000 ft. of buried pipe, four storage tanks, and three pump stations. All pipe is assumed to be buried 5 ft. below ground surface (bgs). Specific data about pipe material and diameter, tank capacity, and pump facilities are included in Appendix C.3.2.1.

Because the imported water is of high quality, little treatment is necessary. The water is pumped to the Ignacio Pump Station where chemicals are added to provide disinfection, fluoridation, and corrosion control. Table C.5 in Appendix C breaks down the annual consumption of each chemical. The treatment plant also includes four small-horsepower pumps, four chemical storage tanks, and 500 ft. of small diameter pipe as part of the chemical delivery system. Detailed information about the treatment system can be found in Appendix C.3.2.2.

Treated water is pumped through a distribution system to the customer. The distribution system consists of approximately 4.5 million ft. of pipe, 8,500 fittings, 60,000 valves, 98 pump stations, and 132 water tanks. Specific information about these components of the MMWD's distribution system is discussed in detail in Appendix C.3.2.3. This system is also used to distribute water obtained from rainfall. As a result, only 22% of the energy use and environmental emissions associated with the distribution are allocated to the imported water system.

Material use inventory data which is entered into the WEST is summarized in Table C.9. Equipment use data is summarized in Table C.10. Electricity use data is summarized in Table C.21.

2.1.3.2.2 Desalinated Water

The MMWD desalination system, as planned, would draw water from the San Francisco Bay and treat it through a RO process. The system would supply 5,000 to 15,000 AF a year; the analysis assumes the system will provide 10,000 AF per year.

The seawater intake and pumphouse would be constructed at the end of a pier which extends 2,000 ft. into the bay. Six pumps with adjustable frequency drives would be needed to supply the necessary influent water. Approximately 10,000 ft. of large-diameter pipe, nine fittings, and five valves would be required to connect the intake to the treatment plant. The supply system is described in more detail in Appendix C.3.3.1.

The desalination process would involve several steps. Influent water would first be pretreated. Coagulants would be mixed with influent water prior to flocculation, sedimentation, and filtration using multi-media filters and cartridge filters. Pretreated water would then be processed through a two-pass RO process. Concentrated brine, the waste product of the RO process, would be discharged through an ocean outfall. Disinfecting chemicals would be added and waters held in a chlorine contact basin to achieve the necessary disinfection. Corrosion and pH control chemicals would be added to effluent water before it is distributed to customers. The treatment process is illustrated in Figure C.2 in Appendix C. Treatment system component sizes and annual chemical consumption are summarized in Tables C.11 and C.12. Additional treatment system description can be found in Appendix C.3.3.2.

The treated water would then be distributed using the existing potable water distribution system; however, approximately 70,000 ft. of additional pipelines, four storage tanks, and three pump stations would be constructed to connect the desalination plant to the existing system. The remainder of the potable water distribution system would be as described in Section 2.1.4.1.2. Additional distribution system information is available in Appendix C.3.3.3.

Material use inventory data which is entered into the WEST is summarized in Table C.14. Equipment use data is summarized in Table C.15. Electricity use data is summarized in Table C.21.

2.1.3.2.3 Recycled Water

The recycled water (700 AF annually) is taken from the effluent of a wastewater treatment plant located in the service area and operated by Las Gallinas Valley Sanitary District. The water is assumed to be transported from the wastewater plant to the recycling facility through 2,500 ft. of pipe, four fittings, and one isolation valve. One pump is necessary to transport the water. The recycled water supply system is further described in Appendix C.3.4.1.

The wastewater effluent is mixed with coagulants and filtered through dual-media filters. Corrosion and pH control chemicals and disinfectant are added to the treated water prior to discharge to the distribution system. Table C.6 provides annual chemical use at the facility; Appendix C.3.4.2 describes the treatment process in more detail.

The non-potable distribution system consists of approximately 25 miles of pipe, 250 fittings, 40 valves, three storage tanks, and four pump stations. Additional information is available in Appendix C.3.4.3.

Material use inventory data which is entered into the WEST is summarized in Table C.19. Equipment use data is summarized in Table C.20. Electricity use data is summarized in Table C.21.

2.1.3.3 City of Oceanside Water Department

The OWD, located in northern San Diego County, imports 92% of its water supply from sources located hundreds of miles from the service area. The utility also provides almost 8% of its water supply by desalinating brackish groundwater through an RO process. The remaining water (less than 1% of total water production) comes from a small recycled water plant that filters effluent from a wastewater treatment plant. Appendix C.4 summarizes the OWD water supply system in detail. Water costs are included in Table 3.

The OWD data was obtained from the following sources: (MWD 1996; MWD 2000; MWD 2004; OWD 1999; OWD 2001; OWD 2003; OWD 2004; SDCWA 2003; SWP 2002; and Wilkinson 2004).

2.1.3.3.1 Imported Water

The OWD imports the vast majority of its water supply (30,200 AF per year) from the Colorado River Aqueduct (CRA) and the State Water Project (SWP). The water is pumped through vast aqueducts over steep terrain to the OWD service area from both sources. The imported water system utilizes pipelines owned and operated by the California Department of Water Resources, the Metropolitan Water District of Southern California (MWD), and the San Diego County Water Authority (SDCWA). The details of the imported water supply system are summarized in Appendix C.4.2.1.1 for the CRA, Appendix C.4.2.1.2 for the SWP, Appendix C.4.42.1.3 for the San Diego Canal, and Appendix C.4.2.1.4 for the San Diego County Second Aqueduct. Each section includes details about the aqueduct design, reservoirs, and pump stations.

The OWD's imported water is treated either at Weese Filtration Plant (owned by the OWD) or Skinner Filtration Plant (owned by MWD). The treatment processes at each plant are similar and involve coagulation, flocculation, filtration, and disinfection. Annual chemical use at the Weese and Skinner Plants are summarized in Tables B.29 and C.31, respectively. More detailed information about the treatment system can be found in Appendix C.4.2.2. The Weese Plant is discussed in Appendix C.4.2.2.1 and the Skinner Plant in Appendix C.4.2.2.2.

Treated water is pumped through a distribution system to the customer. The distribution system consists of approximately 3 million ft. of pipe, 4,900 fittings, 9,000 valves, 9 pump stations, and 12 water storage tanks. Specific information about these components of the OWD distribution system is discussed in detail in Appendix C.4.2.3.

Material use inventory data which is entered into the WEST is summarized in Table C.36. Equipment use data is summarized in Table C.37. Electricity use data is summarized in Table C.43.

2.1.3.3.2 Desalinated Water

The OWD desalination system, which withdraws brackish groundwater from the Mission Basin aquifer, supplies about 2,700 AF a year. The supply system consists of 5 production wells, 3 monitoring wells, over 15,000 ft. of pipe, 15 valves, and 7 pumps. The supply system is described in more detail in Appendix C.3.3.1.

The desalination process involves several steps. Influent water from 3 wells is pretreated with pH control and cartridge filters prior to undergoing a two-pass RO process. Desalinated water is blended with filtered water from the other two wells. The blended water is treated through air strippers. Finally, the water undergoes pH control and disinfection before entering the distribution system. The treatment process is illustrated in Figure C.15 in the Appendix. Annual chemical consumption is summarized in Tables C.38. Additional treatment system description can be found in Appendix C.4.3.2.

The treated water is distributed using the existing potable water distribution system described in Section 2.1.4.2.2. Material use inventory data which is entered into the WEST is summarized in Table C.39. Equipment use data is summarized in Table C.40. Electricity use data is summarized in Table C.43.

2.1.3.3.3 Recycled Water

The recycled water (80 AF annually) is taken from the effluent of the San Luis Rey Wastewater Treatment Plant. The treated water is used primarily for irrigation and groundwater recharge. The water is assumed to be transported from the wastewater plant to the recycling facility through 500 ft. of pipe, four fittings, and one isolation valve. One pump is necessary to transport the water. The recycled water supply system is further described in Appendix C.4.4.1. The wastewater effluent is filtered through a sand filter. Appendix C.4.4.2 describes the treatment process in more detail. The non-potable distribution system consists of approximately 11,100 ft. of pipe, 21 fittings, and 6 valves. Additional information is available in Appendix C.4.4.3. Material use inventory data which is entered into the WEST is summarized in Table C.41. Equipment use data is summarized in Table C.42. Electricity use data is summarized in Table C.43.

2.1.4 Model Evaluation

In order to better understand and qualify the results produced by the model, WEST was evaluated based on sensitivity, uncertainty, and data quality, as described in the following.

2.1.4.1 Sensitivity Analysis

Sensitivity analyses were conducted on appropriate variables by varying a parameter of interest within a reasonable range and holding other parameters constant. The model was then rerun with the updated parameters. This process identifies processes or parameters which contribute most significantly to the final results and provides a more complete understanding of the model. The sensitivity analysis was done deterministically. A probabilistic sensitivity assessment is recommended as a future improvement to the study. Sensitivity analyses are discussed further in the Discussion section.

2.1.4.2 Uncertainty Analysis

A qualitative assessment to determine the sources of uncertainty was completed. Sources of uncertainty were identified. However, the effect of the uncertainty on the results was not estimated. A quantitative uncertainty assessment is recommended in the future. Uncertainty is discussed in the Discussion section.

2.1.4.3 Data Quality

A qualitative assessment of the quality of data used in the analysis is presented in the Discussion section. Table 4 presents the criteria used to assess data quality (Junnila 2003). These criteria were used to analyze the data quality for the case studies analyzed. Numerical values were assigned to all data used in the model to evaluate the quality of the results. Data quality is discussed in the Discussion section.

Table 4. Data Quality Criteria

Indicator score	1	2	3	4	5
Acquisition method	Measured data	Calculated data based on measurements	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Non-qualified estimate
Independence of data supplier	Verified data, information from public or other independent source	Verified information from enterprise with interest in the study	Independent source, but based on non-verified information from industry	Non-verified information from industry	Non-verified information from the enterprise interested in the study
Representative-ness	Representative data from sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from smaller number of sites but for adequate periods	Representative data from adequate number of sites, but from shorter periods	Data from adequate number of sites, but shorter periods	Representativeness unknown or incomplete data from smaller number of sites and/or from shorter periods
Temporal correlation	Less than 3 years of difference to year of study	Less than 5 years difference	Less than 10 years difference	Less than 20 years difference	Age unknown or more that 20 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study, but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials, but same technology	Data on related processes or materials, but different technology

Source: Junnila 2003.

2.2 Project Tasks

The specific tasks undertaken as a part of this research are as follows:

2.2.1. Develop an LCA model of water supply systems

The research team developed a conceptual model of the water treatment system and all processes and components that comprise it. The study evaluated emissions and energy use during the construction, operation, and maintenance phases of the alternative water supply systems. The decommissioning phase was not included, because information was not available and a prior study determined that it contributes less than 1% to the overall environmental burden (Friedrich 2002).

Models were developed to compare imported, desalinated, and recycled water. The first two processes provide potable water, while recycled water is a non-potable source generally used for irrigation, and commercial or industrial applications. However, the three water sources are compared on an equal basis by water planners, because each gallon of recycled water offsets water needed for potable uses, and two-thirds of urban water use is for non-potable applications (Okun 1997).

A 100-year time horizon was chosen for the study because it reflects the life of the longest-lasting infrastructure of the water supply system (e.g., dams and treatment plants). System components with shorter service lives (e.g., pumps, RO membranes, valves) are assumed to be replaced at the end of each service life until the 100-year time horizon is completed.

To get meaningful results from the analysis, the energy use and environmental impacts must be measured by a common functional unit. For this study, the comparison was made between energy use and emissions for the delivery of 100 AF of water to the end-user, the approximate size of the smallest system of a case study. One hundred AF is equivalent to approximately 32,600,000 gallons, or over 123,000,000 liters.

The urban water systems were evaluated to determine economic costs, energy consumption, and related environmental emissions (CO_2 equivalents [CO_2eq.] and GWP, SO_x, NO_x, PM, VOC, and CO) for all alternatives. Results in these terms are useful for technical and public policy decision-making.

Finally, the conceptual model was translated into an analytical model that accounted for all energy inputs to and related environmental outputs from the system. The WEST model is discussed in Section 2.1.2. A detailed discussion of the WEST model is included in Appendix B.

2.2.2. Compile and evaluate model parameter data

Process-based LCA was performed for the process of constructing and maintaining the infrastructure, for operation of all aspects of the water supply system, and for electricity production. Data required for the LCA study of the infrastructural effects were obtained from construction and water system cost estimating guides, publicly available environmental data, and equipment manufacturer’s information. EIO-LCA was used to determine energy use and emissions from material production, including fuel used for vehicles, concrete and other construction materials, pumps, blowers, and steel or iron piping.

2.2.3. Compile and evaluate case study data

Two water utility districts were selected as case studies. These are: (1) the MMWD located in Marin County in the San Francisco Bay Area, and (2) the OWD in northern San Diego County. Case study information is summarized in Section 2.1.4, and Appendix C details the case information further.

2.2.4. Conduct uncertainty analyses on results

A qualitative assessment to determine the sources of uncertainty was completed. Sources of uncertainty were identified and will be the focus of a quantitative uncertainty analysis using Monte Carlo analysis. The sources of uncertainty identified are described in the Discussion section.

2.2.5. Conduct sensitivity analyses on results

Sensitivity analyses were conducted on appropriate variables deterministically changing particular parameters in the model and then observing the changes in the results. Sensitivity analyses focused on material service lives (i.e., how long a given component such as a pump is expected to last). More comprehensive sensitivity analyses will be conducted in the future to evaluate which parameters most affect the results quantitatively. Additional information and results are provided in the Discussion section.

2.2.6. Make recommendations for water supply planning decisions

Based on the results from our LCA model and uncertainty and sensitivity analyses, researchers made recommendations regarding which alternative water sources should be pursued under particular conditions. The effects on water supply choices were determined. Recommendations are provided in the Conclusions and Recommendations section of this document.

2.2.7. Disseminate research results

Results concerning economic costs, energy use, and related environmental emissions for imported, desalinated, and recycled water are published in this final report to the Public Interest Energy Research- Environmental Area (PIER-EA). In addition, the results were presented at two conferences: the Society for Environmental Toxicology and Chemistry (SETAC) Europe Annual Conference in Prague, Czech Republic, on April 18–22, 2004; and the Air and Waste Management Association (A&WMA) Annual Conference in Indianapolis, Indiana, held June 22–25, 2004. The presentation created for the SETAC Conference is found in Appendix A. A refereed article was published as part of the A&WMA proceedings and is available in Appendix B. The presentation created for the A&WMA Conference is in Appendix C. In addition, an article entitled "Life-cycle Assessment of Alternative Water Supply Systems" has been accepted by the *International Journal of LCA.* Future efforts will focus on more widespread dissemination of the methodology and decision support tool created for the study to water supply agencies and policy makers.

3. Discussion

The purpose of this study was to conduct a LCA of two municipal water districts, specifically focusing on the economic implications, energy requirements, and air emissions due to energy consumption resulting from importing, recycling, and desalinating water. This analysis also includes the energy implications of material consumption and its supply chain, but decommissioning was not included, because of a lack of information. To conduct the LCA for the two case studies, a computer-based decision support tool, WEST, was created. WEST is described in Section 2.1.2 and in Appendix B.

The economic implications of the different water sources as well as emission and energy use factors for the different water sources for both case studies are shown in Table 3. As indicated in Table 3, desalination is the most expensive and the most energy intensive of the water supply alternatives, primarily due to high electricity and maintenance costs. Emission factors for the desalination system are the largest for all analyzed substances. In both cases, VOC emissions from desalination systems are over 14 times larger than from the imported water systems and 16 to 18 times larger than from the recycled water systems. This is mainly due to the level of VOC emissions during the production of RO membranes. For the other air emissions, desalination of water produces 2 to 7 times more emissions than the other alternatives.

The high amount of energy needed for desalination systems is attributable to the RO systems in place. The RO process requires water under high pressure to be run through a membrane to remove salts. Significant electricity is required to pump water to the necessary pressure. Energy required to manufacture membranes, chemicals, and other maintenance materials also increases energy use. At the MMWD, desalination uses three times more energy than recycled water and five times more than imported water. The OWD desalination system uses one-half of the energy and emits about one-half of the emissions of the MMWD. However, it is still twice as energy intensive as water importation or recycling. The reason for the differences in desalination energy demand between the two utilities is that they use different saltwater sources. Marin County is processing water from the San Francisco Bay. The assumed design total dissolved solids (TDS) concentration of the influent is 32,000 milligrams per liter (mg/l) but the actual TDS varies seasonally and may be as low as 10,000 TDS. On the other hand, the brackish groundwater used in Oceanside has a TDS of approximately 1,500 mg/l. More energy is required to remove the salt from the high salinity seawater. Also, membranes and other process equipment are replaced more often. Recycling water is more energy intensive in Marin County than in Oceanside, but the results for imported water are similar.

Figure 5 shows the graphical comparison of the GWP of the two utilities in CO_2eq. For the MMWD, desalination produces almost three times the GWP of recycled water and five times that of imported water. For the OWD, desalination has twice the GWP of recycling or importing water. Desalination in Marin County has twice the GWP compared to Oceanside because of the different salt water sources. Recycling is also twice as GWP intensive in the MMWD system because it is more complex, and therefore requires significantly more material and energy consumption. The results for imported water are similar.

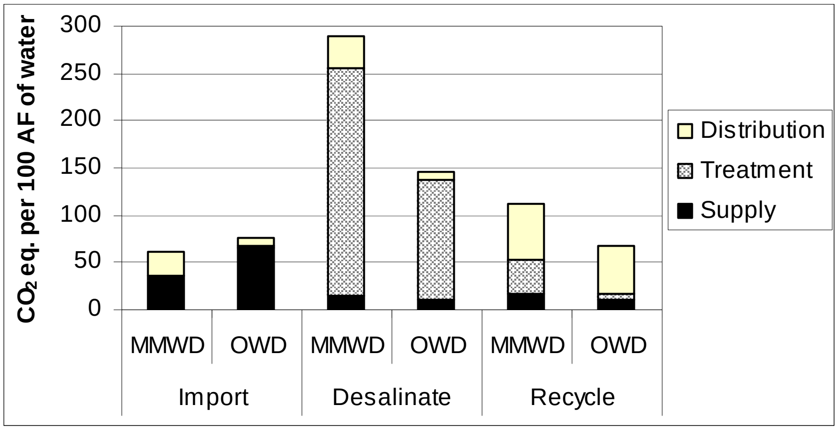


Figure 5. Global warming potential of water supply alternatives by water supply phase

Researchers conducted a comparison of the water supply phases, and Table 5 presents these results. Figure 5 shows that treatment is not a significant contributor to the imported water system for either case—especially for the MMWD, which uses a simpler treatment process. Treatment contributes less than 5% to overall GWP in both cases. However, treatment is the largest contributor to the desalination emissions in both MMWD and OWD, because of the energy intensity of RO systems. Treatment comprises 83% of the MMWD's GWP and 88% of the OWD's GWP. The MMWD system, which requires additional distribution infrastructure to be used solely for desalinated water, attributes 12% of its GWP to the distribution phase, while for the OWD it is only 5%.

Distribution is the largest GWP contributor to both recycled water systems (53% for the Northern California utility and 74% for the Southern California utility). The water treatment plants are located near the wastewater treatment plants from where they obtain their water, minimizing the supply phase impacts, and they have relatively simple treatment processes (i.e., filtration and disinfection at the MMWD [32% of emissions] and filtration only at the OWD [12% of emissions]). However, because wastewater treatment plants tend to be located at lower elevations to minimize energy necessary to collect sewage, distributing recycled water tends to require significant pumping.

Table 5 shows the emissions factors for energy use and GWP for the different water supply and life-cycle phases. These results provide additional insight into the results provided in Table 3. Figure 6 illustrates the results for GWP by life-cycle phase.

Table 5. Energy use and GWP factors for life-cycle and water supply phase

Energy Use Factors (GJ/100 AF) by Life-cycle and Water Supply Phase						
	Import		Desalinate		Recycle	
	MMWD	OWD	MMWD	OWD	MMWD	OWD
Life-cycle Phase						
Construction	73	40	163	82	65	38
Operation	508	840	2192	1249	1022	765
Maintenance	207	62	1528	640	130	48
Water Supply Phase						
Supply	442	811	186	127	205	122
Treatment	12	29	3247	1742	259	100
Distribution	334	102	450	102	753	629

GWP Factors (Mg CO_2 eq./100 AF/pipe mile) by Life-cycle and Water Supply Phase						
	Import		Desalinate		Recycle	
	MMWD	OWD	MMWD	OWD	MMWD	OWD
Supply						
Construction	0.02	0.01	0.3	0.1	0.2	2
Operation	2	5	7	3	34	95
Maintenance	0.01	0.003	0.3	0.2	0.4	5
Distribution						
Construction	0.02	0.005	0.02	0.005	0.1	0.7
Operation	0.02	0.001	0.05	0.001	2	23
Maintenance	0.07	0.01	0.06	0.01	0.07	0.8

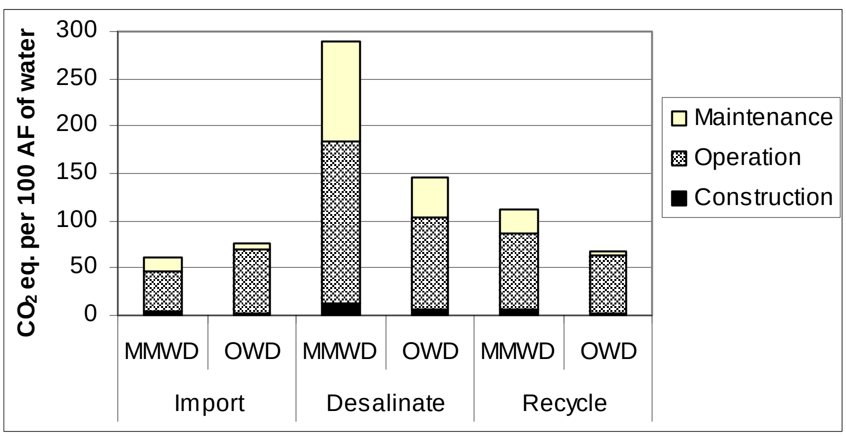


Figure 6. Global warming potential of water supply alternatives by life-cycle phase

Figure 6 highlights the contribution of each life-cycle phase to the final result. The operation life-cycle phase uses the most energy and creates the most emissions, followed by the maintenance phase. Construction effects are considerably less significant. System operation comprises 60% to 91% of the total GWP result for all cases. Maintenance accounts for 5% to 36% of the total GWP. Construction accounts for 4% to 9%. The maintenance phase most affects the desalination systems (36% and 28% in the MMWD and the OWD systems, respectively), because the treatment process includes more components that must be replaced regularly (e.g., RO membranes, cartridge filters). The MMWD GWP is larger, because components from a seawater desalination system will be replaced more frequently than for a brackish water system. Maintenance of the MMWD imported water system is also relatively high (24%) because of distribution system complexity.

As shown in Figure 6, for imported water, the effects of construction and maintenance are smaller for the OWD case study due to economies of scale: the supply system provides water to the entire region and the effects are widely distributed. Recycled water results are also smaller for construction and maintenance in the OWD case study, but for a different reason. In this case, the OWD recycling system is simpler and requires fewer routine inputs (i.e., filtration only versus filtration and disinfection for the MMWD).

The results were also broken out by activity to allow a more thorough understanding of the results. Figure 7 provides the results as contributed by each of the four considered activities: (1) material production, (2) material delivery, (3) equipment use, and (4) energy production. In all cases, energy production is the largest contributor, comprising 56% to 69% of the total result. Material production is also a significant contributor, accounting for 30% to 44% of the result. Material production is most significant for desalination, which has more components requiring routine replacement. Material delivery and equipment use are negligible in all cases, contributing less than 0.6% to the overall emissions.

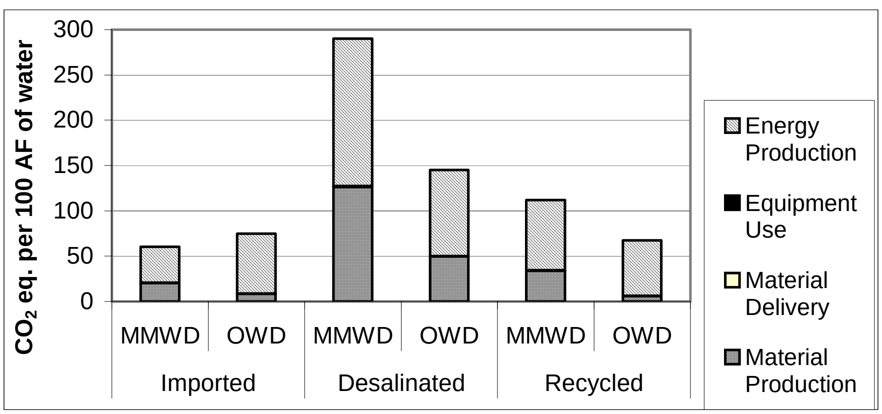


Figure 7. Global warming potential of water supply alternatives by activity

The effects of the separate distribution systems were also evaluated. Based on Figure 5, the emissions per 100 AF of water production for the recycled water distribution systems are higher than for the imported and recycled water distribution systems. In the case of MMWD, the GWP created by the recycled water distribution system per 100 AF of water is approximately 5 times greater than the GWP created by the desalinated and imported water systems. The results are affected by the scale of the systems. The MMWD recycled water system produces over ten times less water than the imported water system, while the pipe length allocated to recycled water is only 7.5 times less than the imported water system. In addition, because of the low emissions from the supply and treatment systems, recycled water remains a competitive and preferable source of water over desalinated water and, in some cases, imported water.

To determine the effects of scale on the environmental results, GWP were normalized by length for supply aqueducts and distribution pipelines for comparison. Though operation phase results vary directly with the volume of water processed, the emission factors for the construction and maintenance phases should also reveal how the systems are affected by economies of scale. For instance, construction and maintenance of the imported water supply system used by both utilities have much lower emission factors than the same for the smaller desalinated and recycled water supply systems. The emission factors for construction and operation of the distribution portion of the recycled water systems are larger than for imported and desalinated water, because the distribution system for recycled water is separate and used only for non-potable water, and therefore is much smaller. The imported and desalinated water distribution systems have similar emissions, because they both use the conventional potable water distribution system. The result indicates that environmental emissions and energy use will be inversely affected by system scale. However, additional case studies are needed to provide more conclusive and more specific results.

A sensitivity analysis was conducted to determine the effects of changes in material service life and energy mix. Sensitivity analyses were conducted to determine how changes in critical parameters would affect the final results. In one analysis, the model was rerun after the service life for capital components was multiplied by 150%, thus reducing component replacement frequency, especially for materials with short service lives such as RO membranes and cartridge filters. This sensitivity analysis was conducted using data for the MMWD system. Increasing service life reduced the effects of the construction and maintenance phases by 7% to as much as 82%. The operation phase was unaffected, because it includes no capital investments (materials) that need to be annualized. In the construction phase, the effects were reduced by approximately 30% for all substances, water supply phases, and water sources, with the exception of desalination treatment. Desalination treatment reductions were only 3% to 11% because the system is composed of fewer materials with long service lives (greater than 75 years). The maintenance phase effects were found to be higher (62%–82%), due to repeated purchases of certain components (e.g., pumps, valves, fittings). Again, desalination treatment is the exception (1%–8% reductions) for reasons already mentioned.

The energy mix assumed in the model also may affect the outcome of the results. For example, using emission factors for Florida, another state where similar water sources are considered, would increase emissions caused by electricity production by a factor of 2 for GWP, a factor of 6 for NO_x, and a factor of more than 30 for SO_x. The changes would primarily affect the operation phase. The energy mix is the sole reason for the difference. California's electricity is produced primarily using natural gas (48.7%), nuclear power (18.6%), hydropower (16.8%), and renewables (12.9%) (USDOE 2004). Coal represents only 1.3% of generation. Florida, on the other hand, obtains 25.7% of electricity from coal plants and 43.8% from dual-fired (combination of coal, natural gas, and petroleum) plants. Conversely, an energy mix with certain renewable energy sources included, i.e., wind, may have lower GWPs.

To identify areas where uncertainty affects the study outcome, a qualitative uncertainty assessment was conducted. The uncertainty assessment did not include quantifying the extent to which the results were affected. Sources for uncertainty in the parameters used in the models include the service life of component parts, material costs, emission factors, and environmental valuation estimates.

A data quality assessment was conducted to further understand the limitations of the assessment. The data used for the cases studies were not ideal. Tables 6 and 7 summarize the data quality for the MMWD and the OWD systems, respectively.

Table 6. MMWD data quality assessment

	Acquisition Method	Independence of data supplier	Representativeness	Data age	Geographical Correlation	Technological Correlation
Equipment Use	4	1	4	1	2	2
Energy Use	3	1	3	1	2	1
Material Delivery	5	1	4	1	2	1
Cost	4	1	4	1	3	2
Material Production						
Imported						
Supply	3	1	2	1	1	2
Treatment	3	1	2	1	1	2
Distribution	3	1	2	1	1	2
Desalinated	3	1	2	1	1	2
Recycled	4	1	3	1	1	2
Chemical Use						
Imported	4	1	3	1	2	2
Desalinated	1	1	2	1	2	2
Recycled	4	1	3	1	1	3
Average	3.4	1.0	2.8	1.0	1.6	1.9
Maximum quality	1	1	1	1	1	1
Minimum quality	5	5	5	5	5	5

For both systems, data quality was problematic. In particular, detailed information about the recycled water treatment process was unavailable, and therefore was estimated based on industry practice. Chemical use at the imported and recycled water plants was estimated based on information from other facilities, especially the OWD treatment plants.

Cost estimates for most materials, except chemicals, were based on construction industry standards. Because the exact specifications for equipment like pumps, flowmeters, and valves were unavailable, costs were averaged among similar model types. Some costs (e.g., large-horsepower pumps, large-diameter pipe, and some chemical storage tanks) were extrapolated from known costs based on an equation which is accurate for order-of-magnitude estimates (see Equation B.5). Cost estimates affect results for material production.

Table 7. OWD data quality assessment

	Acquisition Method	Independence of data supplier	Representativeness	Data age	Geographical Correlation	Technological Correlation
Equipment Use	4	1	4	1	2	1
Energy Use	3	1	3	1	2	1
Material Delivery	5	1	4	1	2	1
Cost	4	1	4	1	3	2
Material Production						
Imported						
Supply	2	1	2	1	1	2
Treatment	2	1	2	1	1	2
Distribution	2	1	2	1	1	2
Desalinated	2	1	2	1	1	2
Recycled	4	1	3	1	1	2
Chemical Use						
Imported	1	1	2	1	2	2
Desalinated	1	1	2	1	2	2
Recycled	4	1	3	1	1	3
Average	2.8	1.0	2.8	1.0	1.6	1.8
Maximum quality	1	1	1	1	1	1
Minimum quality	5	5	5	5	5	5

In addition, material delivery nodes and distances were assumed, because supplier information for individual components was not available. Also, construction equipment use was estimated based on industry equipment productivity (Means 1997). The assessment does not account for site-specific working conditions (e.g., soil conditions). Furthermore, only a limited selection of equipment was analyzed.

Two factors contributed to difficulties in collecting data: security concerns that prevented full disclosure and lack of data collection by the water utilities. Since September 11, 2001, detailed data about water systems is protected for security reasons. In order to get a detailed and complete inventory of what is involved in the water system, it would be necessary to visit the facilities, review engineering documents, and obtain other detailed and possibly sensitive information. For this analysis, the utilities evaluated were asked to provide the information for the sake of research. In the future, when utilities themselves are interested in the quality of the result, better data may become available.

In addition, utilities may not track all of the data needed for an accurate LCA. For example, information about energy use is not necessarily tracked at a facility level. If future research was focused on specific water supply processes (e.g., disinfection), energy use details would not be available. In addition, because many water supply and distribution systems were constructed almost one hundred years ago, an inventory of materials and details of construction are no longer available.

In addition, water utilities track limited details about system operation. Peter Gleick of the Pacific Institute agrees that better water data are needed (Gleick 2003). In some cases, water data simply are not collected, and are therefore not available for evaluation. When the data are collected, the information from different utilities or areas varies in quality and scope. The accuracy of much of the water data available cannot be verified. Utilities need more accessible, detailed, and targeted operations data to improve assessment. The lack of data collection is a major barrier to environmental improvement; the fact is that you cannot manage what you cannot measure. Benchmarking is necessary to make improvements.

4. Conclusions and Recommendations

4.1 Conclusions

This research analyzed two typical water supply systems in California using the WEST decision-support tool, a decision support tool for life-cycle analysis. The analysis compares the economic implications, energy requirements, and air emissions due to energy consumption for alternative sources of water for each utility district. As part of the LCA, the energy implications of material consumption and its supply chain (as well as those of the distribution systems) were addressed. Facility decommissioning was not addressed. Based on this study, researchers reached the following conclusions:

Imported Water

- The effects of imported water are highly site-specific, depending greatly on the amount of pumping necessary to transport the water from the source to the treatment facility. For imported water in the case study systems, the greatest environmental effects occur in the supply phase because the majority of energy demand is for pumping for water transmission
- Treatment of imported water is not a significant contributor to energy demand and resulting emissions for either case study, especially for the MMWD, which uses a simpler treatment process.
- For imported water, the effects of construction and maintenance are smaller for the OWD case study, due to economies of scale: the supply system provides water to the entire region and the effects are widely distributed.

Desalinated Water

- The desalination system air emission factors are the largest for all considered substances as well as for energy use, primarily because of the operation of the reverse osmosis (RO) systems in place in the case study utilities. Most of the environmental effects are due to electricity production, but material production (especially that of RO membranes) is also important.
- Treatment is the largest contributor to the desalination emissions in both MMWD and OWD, because of the energy intensity of RO systems.
- Most of the environmental effects from desalination are due to electricity production, but material production is also important.
- The level of environmental effects will be determined by the salinity of the source water. Seawater desalination creates more environmental burden than desalinating brackish groundwater, primarily due to the higher level of energy consumption required to achieve the necessary pressure for treatment.
- The maintenance phase most affects the desalination systems because the treatment process (e.g., RO membranes, cartridge filters) includes more components that must be replaced regularly.

Recycled Water

- Distribution was the largest energy consumption and GWP contributor to both of the recycled water systems studied. The water treatment plants are located near the wastewater treatment plants that supply their water, minimizing the supply phase impacts.
- Treatment was not a significant contributor to environmental effects. Both systems have relatively simple treatment processes (i.e., filtration and disinfection at the MMWD and filtration only at the OWD).
- Because wastewater treatment plants tend to be located at lower elevations to minimize the energy necessary to collect sewage, distributing recycled water to customers tends to require significant pumping.
- Environmental emissions caused by recycled water system construction and maintenance in the OWD case study are smaller than for the MMWD system. The OWD recycling system is simpler and requires fewer routine inputs.
- The emissions per 100 acre-feet of water production and per length of pipeline for the recycled water distribution systems are higher than for the imported and recycled water distribution systems, due to the scale of the systems. Recycled water systems are typically at least an order of magnitude smaller than potable water systems in terms of both water produced and geographic scale. As a result, when environmental emissions are reported in terms of these parameters, recycled water results are higher.
- Due to the low emissions from the supply and treatment systems, recycled water remains an environmentally competitive and preferable source of water over desalinated water and, in some cases, imported water.

WEST

- The WEST, in its current form, has certain limitations. It does not assess all environmental emissions, account for ecological effects, or quantify environmental impacts such as human toxicity. In addition, it does not allow for analyses of alternative infrastructure choices or energy mixes. The short time frame of the project did not allow for complete analyses of all of these issues.
- Generally, utilities and water planners are not aware that it is possible to assess the environmental effects of their systems using LCA; as a result, the analysis is not included in decision-making. For a more comprehensive picture of the costs associated with water supply choices, LCA using WEST or similar methodology should be conducted routinely.

General

- For the MMWD case study, a significant portion of the water supplied to the utility comes from rainfall via reservoirs; this sources averages 72% of the water supply but varies depending on weather conditions. Only the considered sources (imported, desalinated, and recycled water) were included in the analysis.

- Two case studies do not provide enough data to obtain complete and detailed understanding of the environmental effects of water supply systems. More case studies are needed for better understanding.
- The costs associated with the case study water supply indicate that desalination is consistently more expensive than importing water. In the MMWD system, recycled water is the most expensive water source because it is necessary to construct a separate distribution system. Recycled water costs were not available for the OWD system. Table 3 lists specific economic costs.
- Potable water distribution emission factors varied significantly between the two case studies because the OWD distribution system is designed to distribute water by gravity, whereas the MMWD must rely on significant pumping. Furthermore, the MMWD system requires additional construction to connect the desalination plant to the existing distribution system; whereas, the OWD system uses only the existing infrastructure.
- For all case studies and alternatives, the operation life-cycle phase uses the most energy and creates the most emissions. The maintenance phase is also important. Together these two phases produced over 90% of the GWP emissions. Construction effects are considerably less significant.
- In all case studies and alternatives, the energy produced for use in water systems creates the most air emissions for all the considered activities. Material production is also a significant contributor. Material production includes manufacturing of all inputs to the water system (e.g., membranes, filters, concrete, pipes, chemicals) throughout the supply chain. Material delivery and equipment use are negligible in all cases.
- Both parameters of the sensitivity analyses had significant effects on the results. For the change in material service life, the effects were in the construction and maintenance phase. For the energy mix, the effects were primarily in the operation phase.
- The sensitivity analysis indicates that component service life, which is the average time period a system component (e.g., pump or pipe) will remain in use, affects the final outcome of the study. Increasing the component service life reduced the results in the maintenance phases by as much as 82%. The result was expected because the maintenance phase includes all replacement materials installed to keep the system operating, including new pumps, pipes, and valves. Construction phase emissions were reduced by as much as 30%. This sensitivity analysis was conducted by changing the service life deterministically and re-running the model. However, a probabilistic assessment would provide additional useful information. WEST should be improved in the future to probabilistically capture service life variability and its effects on the study outcome.
- Similarly, the selection of an energy mix can greatly influence the results, according to the sensitivity analysis. The study used the average California energy mix. However, if a more fossil-fuel based mix was selected, the emissions of GWP, NO_x, and SO_x would increase for all alternatives. The WEST tool should also be improved to allow the comparison of customized energy mixes. Currently the tool only allows assessment using average electricity generation emissions on a statewide basis.

- The results are affected by data quality. Two factors contributed to the difficulties in data collection and potentially to data quality issues: (1) security concerns that prevented full disclosure, and (2) lack of data collection by utilities. Security concerns primarily affected the detail of information about supply and distribution systems. Lack of data collection by utilities was a more significant limitation. For example, in some cases electricity consumption data were available only on a systemwide basis. Assumptions were made to allocate energy use by the components of the systems. For both case studies, detailed information on the recycled water system was not available, and assumptions had to be made. More specific information would improve the quality of the results by reducing the uncertainty in the numbers. See Section C.2 for more information on general assumptions.
- Results for similar California water systems considering the same alternatives may be different. The outcome will be affected by site-specific issues such as topography, process design, location, distance to water sources, climate, scale, and other factors.

However, the results for the OWD imported water supply case study will be fairly consistent with other Southern California utilities that primarily use water from the Colorado River and the San Joaquin Delta. In fact, the MWD sold over 400,000 AF to the SDCWA in 1998 (SDCWA 2000). The SDCWA is the water wholesaler that provides water to the OWD. Taking this as typical, supplying water to this area consumes over 900,000 MWh, or 1.8% of California's 2002 net electricity generation (USDOE 2004). Assuming the OWD's treatment and distribution systems are typical of other Southern California utilities, water provision to the region consumed 2% of California's 2002 electricity generation.

Water supply decisions are made based on several factors, including economic, political, and reliability concerns. Heretofore, the comprehensive and systemwide life-cycle environmental effects of the water infrastructure have not been a factor in these decisions. The model and tool described herein will allow utilities and other planners to incorporate these effects into their decision processes, and with more informed analyses strive for sustainable solutions.

4.2 Recommendations

The following recommendations can be made based on this research:

Imported Water

- Based on energy considerations, in the case study systems, water importation should be encouraged if supply pumping can be minimized. However, for imported water systems, it is important to note that the environmental effects of withdrawing water from the ecosystem are not captured by the current WEST model. These effects may be significant and should be included in the decision process along with the WEST results.

Desalinated Water

- If desalination is to be pursued in earnest as a water supply alternative in California, efforts should be made to advance desalination technologies so the process is more energy-efficient and the materials are longer lasting.

- Given current process requirements, projects that desalinate brackish groundwater should be encouraged above those that desalinate seawater. However, if the source of brackish groundwater is seawater intrusion, pumping water from the aquifer will exacerbate the problem and should not be encouraged.

Recycled Water

- The results of this analysis indicate that the needs of water end-users in California should be evaluated in the planning process. Water should not always be treated to the potable water standard when a lower-grade product can meet the consumer's needed.
- Standards for most non-potable applications requires little treatment, and therefore energy use, beyond what is required for discharge from the wastewater treatment plant. Recycled water is more environmentally benign than desalination in the case study systems and therefore should be encouraged in areas where it can be provided at a reasonable cost and where consumers for non-potable water exist. However, efforts should be made to minimize distribution system pumping.
- The increasing popularity of indirect reuse (e.g., when recycled water is used to recharge aquifers which are used for potable supply) in California ensures that applications for recycled water exist within most utility service areas.
- Future analyses should evaluate the effects of putting separate piping systems in new construction, so that recycled water can be used for toilet-flushing, landscaping, and similar uses. Such information would help attract and prioritize potential recycled water customers.

WEST

- This assessment of the environmental effects of water systems should be improved and extended in the future to include assessment of other emissions (e.g., emissions to land and water) and impact assessments (e.g., human or environmental toxicity) and to include alternative infrastructure choices. WEST should be improved in the future to better capture service life variability, to allow the comparison of possible energy mixes, and to assess the environmental effects of water supply which are not due to infrastructure.
- Given that hundreds of billions of dollars will be spent on water system infrastructure in the coming decades, the environmental effects of investments could be considerable, and should be minimized. Unfortunately, the case study utilities are not currently using the results of the study. An effort should be made to share the capabilities of WEST with utility directors and other water supply planners, so they can incorporate its results into their future water decisions. The educational campaign should also inform utilities of the importance of considering the externalities associated with their water systems in planning decisions.
- A less complicated (i.e., reduced and simplified) form of the tool should be made available so that it can be used to make "back of the envelope" estimates of the environmental burden of water supply alternatives.

General

- Results for similar California water systems considering the same alternatives may be different. The outcome will be affected by site-specific issues including topography, process design, location, distance to water sources, climate, scale, and other factors.

- Similar studies should be conducted for additional utilities to provide further information about the environmental effects of water systems. For instance, additional case studies could evaluate elements of the systems that are affected by siting and scale.
- Future research should emphasize the areas that create the greatest energy and environmental burden (e.g., desalination, system operation, electricity production, material production).
- Inadequate data quality adversely affected the results of this analysis. To prevent data quality from affecting future studies, additional work should focus on obtaining higher quality, specific data. Utilities should be encouraged to collect data which can be used for this and similar research. This work should be part of an ongoing effort.

This research provides groundwork for future research on the use of energy by water and wastewater systems by identifying the processes that are most energy and pollution intensive in the entire water supply life-cycle. Additional research in this area should be encouraged. The results of this study can be used to target future research in areas where improvements can be made most readily. Furthermore, the research creates a methodology that can be used to analyze other water and wastewater planning decisions. For instance, LCA may be used to improve energy and environmental performance of:

- wastewater infrastructure decisions;
- recycled water systems within facilities;
- alternative water and wastewater treatment processes; and
- centralized and decentralized water and wastewater systems.

4.3 Benefits to California

The research described herein benefits California specifically by evaluating case study utilities' use of imported, desalinated, and recycled water in terms of energy use and air emissions to evaluate the efficiency, cost-effectiveness, and environmental impacts of existing and future systems. California utilities can better target energy savings and emission reductions by evaluating the effects of water supply infrastructure in terms of life-cycle phase (construction, operation, and maintenance), water supply phase (supply, treatment, and distribution), and activity category (material production, material delivery, equipment use, and energy production).

Water supply decisions are based on several factors, including economic, political, and reliability concerns. Heretofore, the comprehensive and systemwide life-cycle environmental effects of the water infrastructure have not been a factor in these decisions. The conceptual model and associated decision-support tool developed in this research will allow utilities and other planners to incorporate these effects and externalities into their decision processes, and with more informed analyses, strive for sustainable solutions. The methodology developed for this research, and the knowledge gained from it, can be applied to other aspects of water and wastewater systems, to further reduce future energy use and environmental emissions in California.

This research provides groundwork for future research on the use of energy by water and wastewater systems by identifying the processes that are most energy and pollution intensive in

the entire water supply life-cycle. California will benefit from this research and from the development of WEST through a better understanding of water systems, and by encouraging the sustainability of the infrastructure and the systems designed to provide water.

5. References

ASCE. 1998. *Water Treatment Plant Design*. 3rd ed. American Society of Civil Engineers and American Water Works Association. McGraw-Hill: New York.

ASE. 2002. Watergy: Taking Advantage of Untapped Energy and Water Efficiency Opportunities in Municipal Water Systems; Alliance to Save Energy/U.S. Agency for International Development.

ATA. 2001. *Annual Report 2001*. Air Transport Association. www.airlines.org/econ/files/2001AnnualReport.pdf . (Accessed April 27, 2004.)

CARB. 2002. "Off-Road Emissions Model: Mailout MSC #99-32." California Air Resources Board. www.arb.ca.gov/msei/msei.html. Accessed May 1, 2002.

California Assembly. 1990. *Urban Water Management Plan Act*. California Assembly Bill 2661.

California Energy Commission. 2003. "Process Energy" Home Page. California Energy Commission. www.energy.ca.gov/process/index2.html. (Accessed January 2003.)

Caterpillar. 1996. *Caterpillar Performance Handbook*. 27th ed. Caterpillar, Inc. Peoria, Ill.

CDWR. 2003. *Guidebook for Implementation of Senate Bill 610 and Senate Bill 221 of 2001*. California Department of Water Resources, October 8. www.owue.water.ca.gov/Guidebook_101003.pdf. (Accessed September 2004).

CMU. 2004. *Economic Input-Output LCA*. Carnegie Mellon University, Green Design Initiative. www.eiolca.net. (Accessed March 2004).

Crettaz, P., O. Jolliet, J. M. Cuanillon, and S. Orlando. 1999. "Life-cycle Assessment for Drinking Water and Rain Water for Toilets Flushing." *Aqua* 48: 78–83.

Curran, M. A. (ed.). 1996. *Environmental Life-cycle Assessment*. McGraw-Hill: New York.

Das, T. 2002. "Evaluating the Life-cycle Environmental Performance of Chlorine Disinfection and Ultraviolet Technologies." *Clean Technologies and Environmental Policies* 4: 32–43.

DWR. 1998. *California Water Plan Update: Bulletin 160-98.* 2 vols. California Department of Water Resources. November.

EEA. 2002. *EMEP/CORINAIR Emission Inventory Guidebook - 3rd ed*. European Environmental Agency. http://reports.eea.eu.int/EMEPCORINAIR3/en. (Accessed April 2004.)

E-GRID. 2002. *The Emissions and Generation Resource Integrated Database (E-GRID2002) Version 1.0, 2000 Data*. U.S. Environmental Protection Agency: Washington, D.C.

Friedrich, E. 2002. "Life-cycle Assessment as an Environmental Management Tool in the Production of Potable Water." *Water Sci. Technol.* 46: 29–36.

Gleick, P. H. 2003. "Water Use." *Annual Review of Environment and Resources.* 28: 275–314.

Graedel, T. E., and B. R. Allenby. 2003. *Industrial Ecology*; 2nd ed.; Prentice Hall: Upper Saddle River, New Jersey.

Hendrickson, C., A. Horvath, S. Joshi, and L. Lave. 1998. "Economic Input-Output Models for Environmental Life-cycle Assessment." *Environ. Sci. Technol*. 32: 184A.

Hermanowicz, S., E. Diaz, J. Coe. 2001. "Prospects, Problems, and Pitfalls of Urban Water Reuse: A Case Study." *Water Sci. Technol.* 43: 9–16.

Herz, R., and A. Lipkow. 2002. "Life-cycle Assessment of Water Mains and Sewers." *Water Sci. Technol.: Water Supply 2*: 51–72.

Huffman, J. 2001. "Water Supply Planning: Marin Municipal Utility District." Presented to Marin Countywide Plan Working Group on November 6, 2001. www.future-marin.org/library.cfm?element=5#Reports. (Accessed March 2003.)

IPCC. 1999. *Aviation and the Global Environment: Aviation Fuels*. Intergovernmental Panel on Climate Change. www.grida.no/climate/ipcc/aviation/109.htm. (Accessed April 27, 2004.)

ISO. 1997. Environmental Management – Life cycle Assessment – General Principles and Framework; International Organization for Standardization.

ISO. 1998. Environmental Management – Life-cycle Assessment – Goal and Scope Definition – Inventory Analysis; International Organization for Standardization.

ISO. 2004. "ISO 14000." International Organization for Standardization. www.iso.ch/iso/en/iso9000-14000/iso14000/iso14000index.html. (Accessed March 2004).

Jeane, P. 2004. Personal communication (electronic mail). Sonoma County Water Agency. February 13 and 23, 2004.

John Deere. 2004. "Construction Equipment" home page. John Deere Corporation. www.deere.com/en_US/cfd/construction/deere_const/crawlers/deere_dozer_selection.html. (Accessed January 2004.)

Junnila, S., and A. Horvath. 2003. "Life-Cycle Environmental Effects of an Office Building." *Journal of Infrastructure Systems***.** 9(4): 10, 2003.

Kauwe, J. 2004. Personal communication (electronic mail). North Marin Water District. February 25, 2004.

Levine, A., and T. Asano. 2004. "Recovering Sustainable Water from Wastewater." *Environ. Sci. Technol. 38*(11): 201A–208A.

Lundie, S., G. M. Peters, and P. C. Beavis. 2004. "Life-cycle Assessment of Sustainable Metropolitan Water Systems Planning." *Environ. Sci. Technol. 38*: 3465–3473.

Mays, L. W., ed. 2000. *Water Distribution Systems Handbook*. American Water Works Association, McGraw-Hill: London.

MBK Engineers. 2002. *Marin Municipal Water District Water Supply Planning Model*. Sacramento, California. August 2002.

Means 1997. *Heavy Construction Cost Data*, 12th ed. Page, J., ed. R.S. Means Corporation: Kingston, Massachusetts.

MMWD. 1990. *Why Desalination May Be Our Best Water Supply Option*. Marin Municipal Water District: Corte Madera, California. 1990.

MMWD. 1995. *Urban Water Management Plan*. Marin Municipal Water District. Corte Madera: California. December 1995.

MMWD. 2003. *Long-Range Capital Plan, 2003-2013- Draft*. Marin Municipal Water District: Corte Madera, California. September 2003.

MMWD. 2004. "Marin Municipal Water District" home page. www.marinwater.org. (Accessed January 2004.)

MUWMP. 2003. *Draft Urban Water Management Plan 2000*. Marin Municipal Water District: Corte Madera, California. February, 2003.

MWD. 1996. *Southern California's Integrated Water Resources Plan*. Metropolitan Water District of Southern California: Los Angeles, California.

MWD. 2000. *The Regional Urban Water Management Plan*. Metropolitan Water District of Southern California: Los Angeles, California. December 2000.

MWD. 2004. "The Metropolitan Water District of Southern California" home page. http://www.mwdh2o.com. (Accessed March 2004.)

NMWD. 2004. "North Marin Water District" home page. www.nmwd.org. (Accessed February 20, 2004.)

OECD. 1997. *The Environmental Effects of Freight*. Organization for Economic Cooperation and Development: Paris, France.

Okun, D. A. 1997. "Distributing Reclaimed Water through Dual Systems." *J. of the American Water Works Association* 89: 13.

OWD. 1999. *Water Master Plan*. ASL Consulting Engineers for Oceanside Water Utilities Department: Oceanside, California. May 1999.

OWD. 2001. *City of Oceanside 2000 Urban Water Management Plan*. Oceanside Water Utilities Department: Oceanside, California.

OWD. 2003. Site visit to Oceanside Water Utilities Department, Oceanside, California. August 6–8, 2003.

OWD. 2004. Tucker, S. Personal communication (electronic mail). Oceanside Water Utilities District. March 24–31, 2004.

Peters, M. S., K. D. Timmerhaus, and R. West. 2003. *Plant Design and Economics for Chemical Engineers*. 5th ed. McGraw-Hill: New York.

Rogers, P. 2004. "Valley Firms to Fight Global Warming." *The Mercury News*; San Jose, March 29, 2004.

Romano, D., D. Gaudioso, and R. De Lauretis. 1999. "Aircraft Emissions: A Comparison of Methodologies Based on Different Data Availability." *Environmental Monitoring and Assessment*. 56: 51–74.

SCWA. 2004. “Sonoma County Water Agency” home page. www.scwa.ca.gov/. (Accessed March 2004.)

SDCWA. 2000. *2000 Urban Water Management Plan*. San Diego County Water Authority, Water Resources Department.

SDCWA. 2003. Nakamura, J., Engineering Department, San Diego County Water Authority. Personal Communication (site visit). San Diego, California. August 7, 2003.

SETAC. 1991. “A Technical Framework for Life-cycle Assessment.” In *Society of Environmental Toxicology and Chemistry Workshop Report*. Smugglers Notch, Vermont.

SETAC 1993. “Guidelines for Life-cycle Assessment: A Code of Practice” In *Society of Environmental Toxicology and Chemistry*. Sesimbra, Portugal.

Sheikh, B., and Parsons Engineering Corporation. 2001. “Seawater Desalination as a Possible Alternative Component of Integrated Water Resources” for Marin Municipal Water District. June 2001.

Sorenson, L. and N. Kilde. 1995. *Waste Treatment and Disposal: Air Traffic*. Risoe National Laboratory, Systems Analysis Department; European Environmental Agency. http://eionet.eea.eu.int/aegb/cap08/b851.htm. (Accessed January 2002).

Stokes, J. 2004. “Life-cycle Assessment of Alternative Water Supply Systems in California.” Unpublished Ph.D. Dissertation. University of California, Berkeley.

SWP. 2002. *Management of the California State Water Project*. Report 132-01. California Department of Water Resources: Sacramento, California.

Theisen, Ron. 2004. Personal Communication. General Manager, Marin Municipal Utility District: Corte Madera, California. February 2004.

URS Corporation. 2003. *Initial Project Screening and Environmental Screening - MMWD Desalination Project*. Oakland, California. May 2003.

USDOE 2004. “State Electricity Profile.” Department of Energy, Energy Information Administration. www.eia.doe.gov/cneaf/electricity/st_profiles/toc.html. (Accessed July 2004).

USDOI. 2003. *Water 2025: Preventing Crises and Conflict in the West*. Dept. of the Interior Bureau of Reclamation: Washington, D.C.

USEPA. 1993. Vigon, B.W. *Life-cycle Assessment: Inventory Guidelines and Principles.* U.S. Environmental Protection Agency: Cincinnati, Ohio.

USEPA. 1995. “Compilation of Air Pollutant Emission Factors AP-42, Mobile Sources, Heavy-Duty Diesel Trucks,” Environmental Protection Agency: Washington, D.C., June 1995. www.epa.gov/otaq/models/ap42/ap42-h7.pdf. (Accessed April 2002.)

USEPA. 1996. “Gasoline and Diesel Industrial Engines- Emission Factor Documentation for AP-42: Compilation of Air Pollution Emission Factors, Vol. 1: Stationary Sources, Section 3.3: Gasoline and Diesel Industrial Engines, Supplement B.” Environmental Protection Agency: Washington, D.C.

USEPA. 1998. Beardsley, M., and C. Lindhjem. *Exhaust Emission Factors for Non-Road Emission Modeling—Compression Ignition*. Environmental Protection Agency: Washington, D.C.

USEPA. 2002. *The Clean Water and Drinking Water Infrastructure Gap Analysis*; U.S. Environmental Protection Agency: Office of Water.

van Tilburg, J., E. Nieuwlaar, and J. Geerts. 1997. "Environmental Analysis for Choosing between a Single or Double Domestic Water Supply." *5th LCA Case Studies Symposium*, SETAC Europe: Brussels, Belgium. 213–220.

Wilkinson, R. 2004. "Methodology for Analysis of the Energy Intensity of California Water Systems." Report to Lawrence Berkeley Laboratory. January 2000. www.es.ucsb.edu/faculty/Wilkinson_EWRPT01%20DOC.pdf. (Accessed May 2004.)

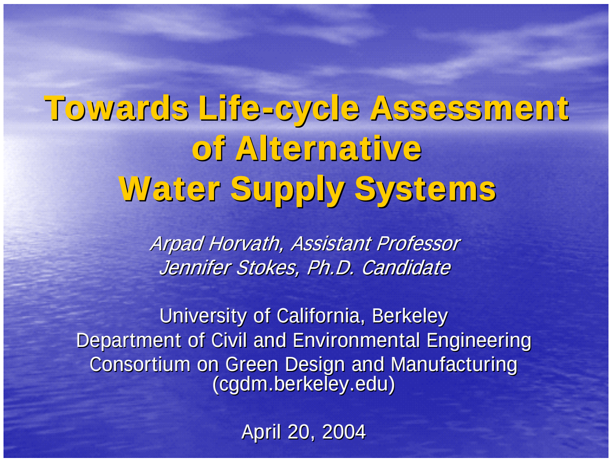
Glossary

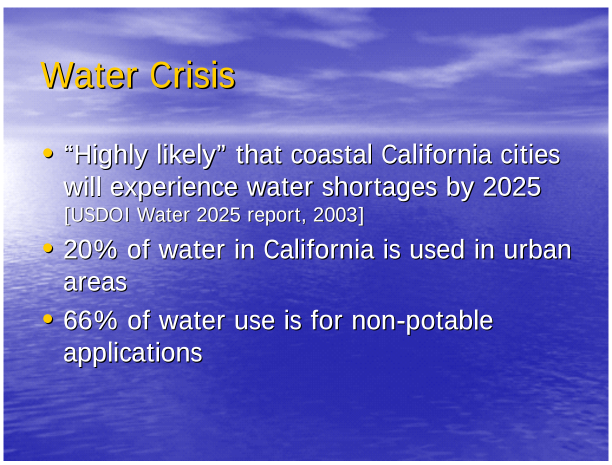
AC	Asbestos concrete
AF	Acre-foot
A&WMA	Air and Waste Management Association
bgs	Below ground surface
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
CRA	Colorado River Aqueduct
DI	Ductile iron
EIO-LCA	Economic input-output life-cycle assessment
EPA	U.S. Environmental Protection Agency
ft.	Foot
ft^2	Square foot
GWP	Global warming potential
hp	Horsepower
in.	Inch
ISO	International Organization for Standardization
kg	Kilogram
LCA	Life-cycle assessment
NO_x	Nitrogen oxides
mg/l	Milligrams per liter
MMWD	Marin Municipal Water District
MWD	Metropolitan Water District of Southern California
OWD	City of Oceanside Water Department
PIER-EA	Public Interest Energy Research- Environmental Area
PE	Polyethylene
PM	Particulate matter
PVC	Polyvinyl chloride
RD&D	Research, Development, and Demonstration
RO	Reverse osmosis
SDCWA	San Diego County Water Authority
SETAC	Society for Environmental Toxicology and Chemistry
SO_x	Sulfur oxides
SWP	State Water Project
TDS	Total dissolved solids
UV	Ultraviolet radiation
UWMP	Urban Water Management Plan
VOC	Volatile organic compounds
WEST	Water-Energy Sustainability Tool

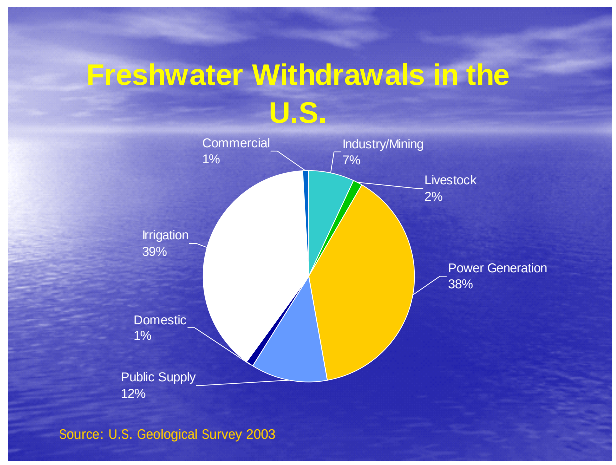
Appendix A. Publications and Presentations

A.1 Presentation at the Society for Environmental Toxicology and Chemistry (SETAC) Europe Annual Conference

The following are the slides used to present the subject research at the SETAC Europe Conference in Prague, Czech Republic, on April 20, 2004.



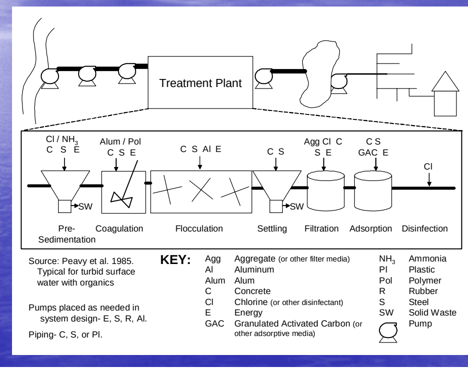




Water Sources

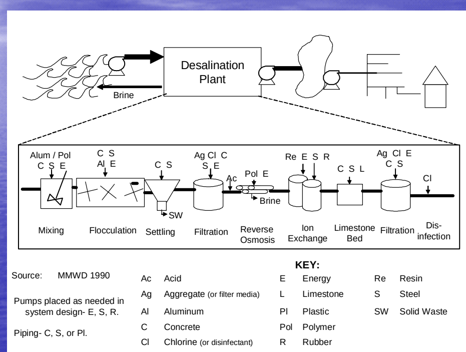
- Imported water is pumped hundreds of miles
  - E.g., from the Colorado river or from lakes in the Sierra Nevada Mountains
  - Appr. 2 MWh spent per million liters of water
- Desalination uses reverse osmosis and is also energy-intensive
- Recycled water treats secondarily treated wastewater to standards appropriate for non-potable use

Water Sources – Imported Water



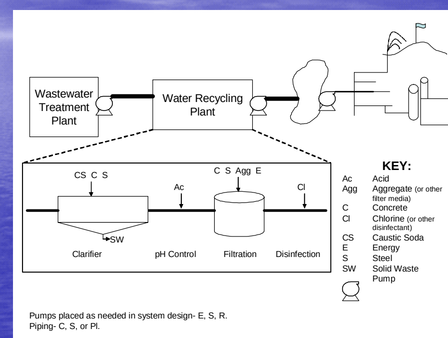
Source: Peavy et al. 1985

Water Sources – Desalinated Water



Source: MMWD 1990

Water Sources- Recycled Water

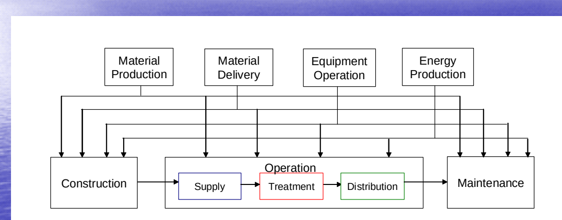


Source: Based on Tchobanoglous et al. 1991

The WEST Tool

- Water-Energy Sustainability Tool
- MS Excel-based *hybrid LCA* model
- Evaluates material production, material delivery, construction processes and equipment use, and energy production
- Provides results for energy use, global warming, and air emissions

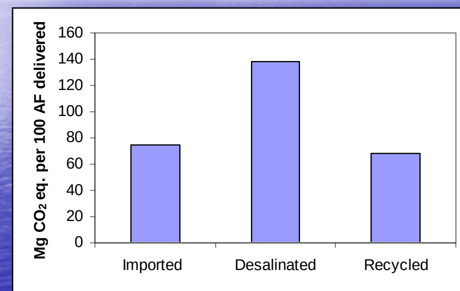
WEST Structure



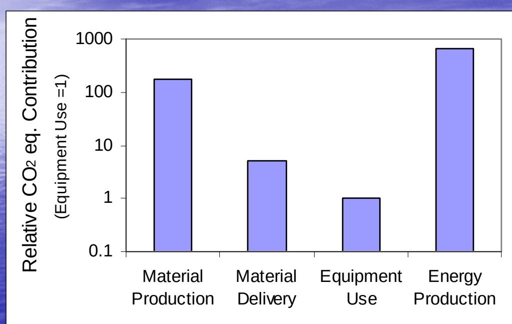
Case Study

- Oceanside, Southern California water utility serving approximately 200,000 people
- Obtains 92% of water from imported sources, 8% from desalinated brackish groundwater, and less than 1% from recycled water
- 65% of water purchased raw from a water wholesaler; 35% is treated by the wholesaler

Comparison of Global Warming Effect Results



Global Warming Effect by Activity



Improvements Needed in the Study

- Life-cycle effects of sludge disposal
- Life-cycle effects of electricity generation (e.g., include mining)
- Life-cycle effects of hydroelectric energy recovery
- Analysis of construction processes is limited and likely underestimated; need to account for varying conditions

A.2 Paper in the Proceedings of the Air & Waste Management Association (A&WMA) Annual Conference

The following article was peer-reviewed and published in the A&WMA 2004 Annual Conference Proceedings, Indianapolis, Indiana, June 22-25, 2004.

Life-cycle Assessment of a Desalination System in California

Paper Number # 183

Jennifer R. Stokes and Arpad Horvath

University of California, Department of Civil and Environmental Engineering

215 McLaughlin Hall, University of California, Berkeley, California 94720

Abstract

Meeting water demand is a key economic and political issue in California. The U.S. government predicts that there will be a water crisis in the state in 20 years if no action is taken. As a result, water utilities are exploring new water sources and policies. Desalination is being considered as a water source by many coastal communities but it is a material- and energy-intensive process. To inform a sustainable water supply decision, an analytical tool was created which analyzes the impact of construction, operation, and maintenance of water supply systems using life-cycle assessment. The tool considers material production and delivery, construction and maintenance equipment use, and energy production through the life-cycle of a candidate water supply system.

This paper demonstrates the capabilities of the decision-support tool by analyzing a hypothetical desalination plant located in coastal California. Construction, operation, and maintenance are included in the analysis. Energy use, global warming potential, and air emissions (nitrogen oxides, particulate matter, sulfur oxides, volatile organic compounds) were estimated over a 50 year time frame and are reported in terms of average annual emissions. The results demonstrated that system operation, particularly of the treatment system, dominates the environmental burden and are caused primarily by electricity use. However, the construction and maintenance phases are significant contributors to particulate matter and volatile organic compound emissions due to material production.

Introduction

California receives approximately 193 million acre-feet (MAF) of water each year through rain and snow[1]. Eighty-seven percent of it either soaks into the ground, flows to the ocean or, by law, must remain in rivers. Of the 25 MAF remaining, urban water use comprises 20%; the remainder is used by agriculture. Urban water demand is expected to grow as the state’s population increases to 40 million by 2010. The state expects to experience a shortage of 4 to 6 MAF by 2010 unless changes are made. For many urban coastal areas of California, the risk of a water supply crisis by 2025 is ranked as substantial or highly likely[2].

Developing new water sources to alleviate this problem will require new infrastructure and new treatment processes. As part of the Water 2025 program, the Department of Interior has committed funds to study and implement desalination projects in the West[3]. Desalination is known to be energy- and material-intensive. Water utilities consider the economic costs of electricity when evaluating the decision to pursue a desalination system. However, the evaluation rarely considers environmental costs, including air emissions that result from the electricity generation and energy use due to material production. Implementing a desalination process requires: installing additional pipelines; constructing treatment facilities; manufacturing pumps, membranes, and other equipment; and producing chemicals used in the treatment processes. Operating construction, maintenance, and transportation vehicles produces tailpipe emissions.

Water supply planning decisions should be made with a sustainable lens considering the environmental effects of the system through its life-cycle. The impact of energy, equipment, and material production and use in the process should be evaluated and considered as a part of the decision-making process. Such an assessment requires a systematic approach such as life-cycle assessment (LCA).

Prior water and wastewater system LCAs have considered the effects of dual piping systems and water recycling in Europe[4], the effects of water efficiency programs in Switzerland[5], the effects of different treatment processes such as disinfection in the U.S.[6] or filtration in South Africa[7], and the effects of material choices and construction methods for distribution piping[8]. Additional LCAs of urban water systems have been conducted, primarily focused on wastewater treatment in Europe[8-13]. In addition, a number of studies have been done on water efficiency and energy use[14,15]. However, a comprehensive assessment of U.S. water supply systems has not been conducted.

In order to quantify air emissions and energy use associated with water systems, a decision-support tool was created by the authors. This tool uses user-defined input data to evaluate emissions and energy use throughout the life-cycle of the system- including construction, operation and maintenance. Decommissioning of the system is not included because sufficient data were not available and it is expected to contribute negligibly to the final result. (One study found that decommissioning contributed less than 1% of the overall environmental burden[7].)

The tool created is useful for several audiences - planners, designers, construction contractors, plant operators, utility administrators, and policy analysts. It can be used to evaluate the effects of a variety of water supply decisions, including:

Choosing materials for infrastructure improvements (e.g., steel versus concrete reservoir, plastic versus iron, steel, or concrete pipe);

Selecting alternative water supplies (e.g., recycled, imported, or desalinated);

- Changing drinking water standards (e.g., central versus point-of-use treatment to achieve a stricter arsenic standard); and

Evaluating alternative treatment processes (e.g., membrane versus dual-media filtration, chlorine versus ultraviolet disinfection).

The tool can also be used to identify areas where energy efficiency improvements can be focused, material use reduced, or environmental burden minimized.

Methodology - LCA description

Water supply planning which considers energy and emission effects requires LCA, a quantitative approach developed to evaluate the impacts of a process from "cradle" to "grave." LCA considers the energy and environmental effects of processes through the life-cycle, including design, planning, material extraction and production, manufacturing or construction, use, maintenance, and end-of-life fate of the product (reuse, recycling, incineration, or landfilling)[16].

The tool uses a hybrid LCA approach combining process-based and economic input-output analysis-based methodology. Each methodology is described in more detail below.

Process-Based Life-cycle Assessment

LCA theory and methodology have been developed and formalized over the last decade[17-21.] LCA involves four steps: goal and scope definition, inventory analysis, impact analysis, and improvement analysis[22, 23]. It is an iterative process; an interpretation of results occurs after each step. Figures 1 and 2 illustrate the process.

Figure 1: LCA Process[22]

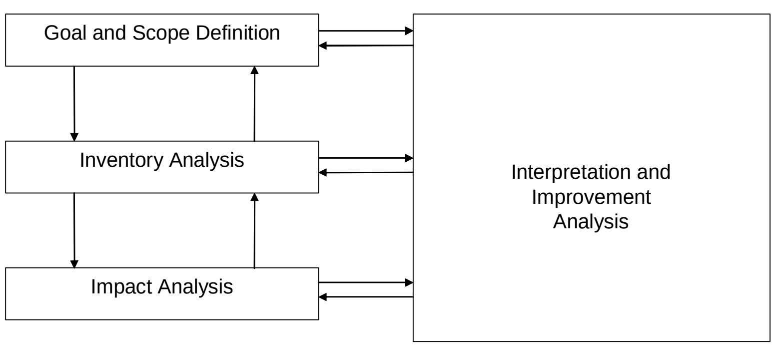
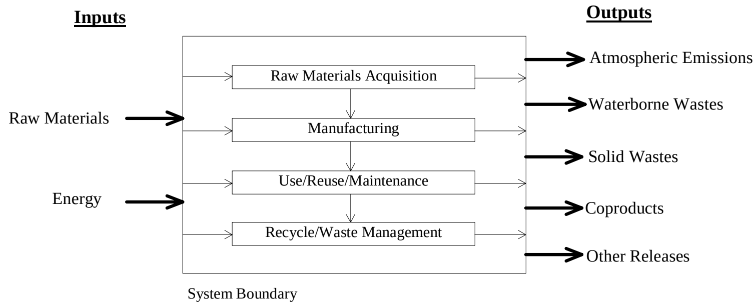


Figure 2: LCA Inventory Analysis Framework[24]



Economic Input-Output Analysis-based Life-cycle Assessment

Economic input-output analysis-based LCA (EIO-LCA) is an alternative matrix-based approach[25,26] that combines the U.S. Department of Commerce's economic input-output model[27] and publicly available resource consumption and environmental emission data[28-30]. As a general interdependency model, the economic input-output model describes interactions between all U.S. economic sectors. For a producer's expenditure in a given economic sector, EIO-LCA estimates how much is spent directly in that sector and in the supply chain, and calculates the associated environmental emissions.

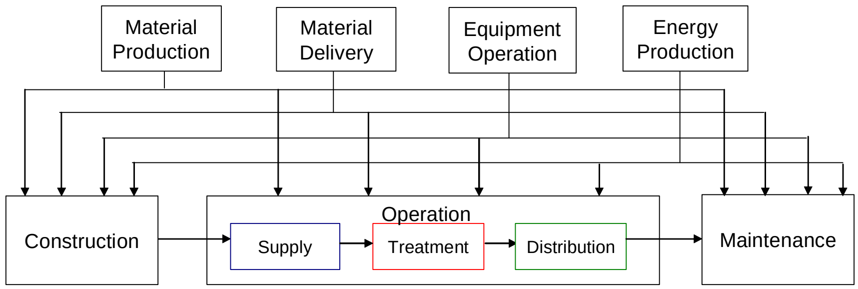
Hybrid Life-cycle Assessment

Hybrid LCA combines the best of process-based LCA and EIO-LCA while minimizing the disadvantages of each. Process-based LCA effectively determines process-specific inputs and outputs but makes including supply chain effects expensive and time-consuming. Conversely, EIO-LCA calculates system-wide supply chain effects but certain sectors may be too aggregated to provide meaningful results (e.g., plastics of all grades are combined into one sector). Hybrid LCA provides a framework for a more comprehensive assessment than using the two methods separately.

Tool Description

A tool was created to evaluate the energy use and environmental burden associated with water supply systems in California for the water supply life-cycle. The tool created by the authors utilizes hybrid LCA methodology, incorporating process-based LCA to estimate emissions due to equipment use and system operation and EIO-LCA to capture the systemwide effects of material production. Figure 3 defines the boundaries of the LCA analysis.

Figure 3: Analysis Boundaries

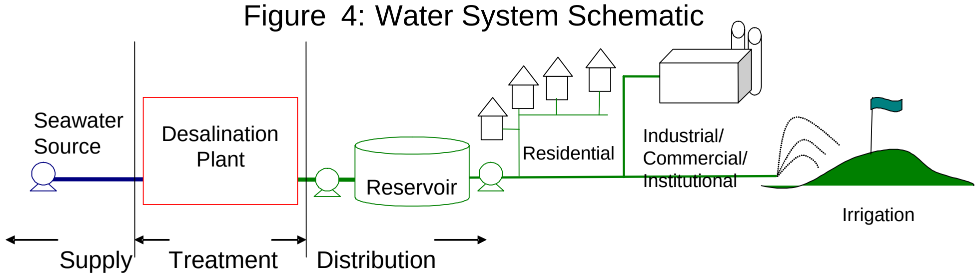


As shown in Figure 3, the tool evaluates energy and material use for four different categories of activities: material production and delivery, equipment use, and energy production. The environmental effects of labor are excluded from the system boundary. Material production assessment allows the user to inventory the materials used in the system and obtain an evaluation of the effects of their manufacture or provision throughout the supply chain. The material delivery component assesses the emissions produced and energy used to transport materials to the end-use location by means of truck, train, ship, or airplane. Equipment use assesses the emissions and fuel use from operating non-delivery equipment, especially construction equipment and maintenance vehicles. Energy production focuses on the impact of producing electricity or fuel (e.g., diesel or gasoline needed to operate vehicles) used in the system.

Each item entered in the tool must be further categorized by user according to the associated life-cycle phase. An item may be used in the construction, operation, or maintenance of the system. The construction phase includes the initial facility building and equipment production and delivery for the entire system as well as construction equipment operation. Operation includes all chemicals and energy used by the system continuously. Maintenance includes replacement parts (piping, pumps, membranes, and filters) and cleaning chemicals for the system.

In addition, each item should be defined as a component of water supply (transporting water from the source to the treatment plant), treatment (ensuring water meets regulatory water quality standards), or distribution (storing water and transporting it to the end-user after treatment). Figure 4 illustrates the general components of a water supply system.

Figure 4: Water System Schematic



The tool is an Excel-based spreadsheet and contains worksheets in four different categories: data entry, data, calculations, and results. The data entry pages allow the user to input data related to their system. A general information page requires the user to define the name and location of the water system being analyzed, the population, service area, and customer demographics of the analyzed system, the major facilities in the system (e.g., treatment plants, reservoirs, and large pumping stations), and model parameters (e.g., analysis time-frame and functional unit).

The user also enters data related to construction, transportation, and maintenance equipment used in the system on a separate worksheet. This page allows the user to define the size, model year, engine capacity, productivity, fuel type, and fuel use of various pieces of construction, transportation, or maintenance equipment. For example, the user can define the excavator model that would be used for construction and the model year of dump truck that would be used for sludge disposal during operation. The worksheet contains a variety of pre-defined equipment characteristics, but the user can define more precise information if desired. Figure 5 captures part of the equipment input worksheet.

Figure 5: Example of Data Entry Worksheet

EQUIPMENT DATA

Instructions

Tables Included:
Equipment Details
Diesel Road Equipment Assumptions
Diesel Non-road Equipment Assumptions

Equipment Details

Activity	Equipment	Brand/Model	Engine Capacity	Power	Productivity	Fuel Consumption	Fuel Type	Emissions Category
Concrete Placement	Concrete Mix Truck	International 5500i	565 hp		41 ton/h	10 mpg	diesel	DR
	Concrete Pump	Schwing BPL1200	476 hp				diesel	NR300TO600
	Concrete Vibrator	Oztec GV-5H	6 hp				gasoline	gasoline
	Rebar Cutter	Multiquip BC-25		1200 watts			electric	Electric
	Rebar Bender	Multiquip MB-25		1200 watts			electric	Electric
Excavation and Earthwork	Large Excavator	Caterpillar 375	428 hp			94 l/h	diesel	NR300TO600
	Small Excavator	John Deere 690E	131 hp			9 l/h	diesel	NR100TO175
	Backhoe Loader	John Deere 710G	118 hp			8 l/h	diesel	NR100TO175
	Vibratory soil compactor	Dynapac CA 262D	150 hp			10 l/h	diesel	NR100TO175
	Grader	Caterpillar 120H	125 hp			8 l/h	diesel	NR100TO175
	Dozer with ripper	Caterpillar D8N	285 hp			19 l/h	diesel	NR175TO300
	Wheel loader	John Deere 644E	160 hp		4 ton/h	11 l/h	diesel	NR100TO175
	Dump Truck	Sterling L8500	250 hp			10 mpg	diesel	DR
Concrete Paving	Slipform paver	Wirtgen SP 250	106 hp			5 l/h	diesel	NR100TO175
	Texture curing machine	Gomaco T/C 400	70 hp			5 l/h	diesel	NR50TO100
Asphalt Paving	Paver	Blaw-knox PF-5510	184 hp			12 l/h	diesel	NR175TO300
	Pneumatic roller		100 hp			7 l/h	diesel	NR100TO175
	Tandem roller		125 hp			9 l/h	diesel	NR100TO175
Meter Reading and	Pickup Truck		NA	NA	NA	17 mpg	gasoline	GR

Blaw-knox PF-5510
Cedarapids CR451
Dynapac F25C
Dynapac F30C
Custom
none

Instructions / Checklist / Entry-Project Info / **Entry-Equipment** / Entry- Material Production / Entry-Material Delivery / Entry-

A separate data entry page is available for each of the four included activities. For material production, the user must enter the material type, cost, quantity used, and service life. Material costs are obtained from a variety of sources[31-33] and are entered in 1997 dollars, the base year of the LCA data. Costs are discounted using the *Engineering News Record's Construction Costs Index* as necessary[32,34].

For material delivery, the user enters cargo weight, the primary and, if necessary, secondary transport modes (i.e., truck, train, ship, or airplane) as well as the distance traveled and number of deliveries made annually by each mode.

For equipment use, the user enters information on vehicle type, amount of use (in either hours or miles depending on vehicle type), and frequency of use. Energy production data entered includes the electricity (in kWh) required to operate the system. Fuel used to operate construction, maintenance, and transportation equipment is calculated automatically on this worksheet based on prior input values.

Data worksheets contain emission factors for material production[25], material delivery[35], equipment use[36,37], equipment characteristics[38], and energy production[25,39]. In addition, some data are available on representative costs for typical system materials[31]. The tool documentation contains additional information on data sources.

The calculation pages combine user-entered information and standard data to determine energy use and air emissions for all categories. Results are displayed both numerically and graphically and are broken down to display information according to life-cycle phase (construction, operation, and maintenance), water supply phase (supply, treatment, and distribution), and activity category (material production, material delivery, equipment use, and energy production). Energy use, global warming potential (GWP), and air emissions (nitrogen oxides (NO_x), particulate matter (PM), sulfur oxides (SO_x), volatile organic compounds (VOC)) are reported in terms of average annual emissions.

Case Study Description

The case study used for this analysis is a water utility serving a hypothetical city in coastal California. The population served by the water utility is 250,000. The water utility obtains approximately 20,000 acre-feet annually (AFA) from imported water, 1,000 AFA from recycled water, and 10,000 AFA from desalinated seawater. The desalination portion of the water system is the focus of this assessment.

Desalinated water is obtained from a low-salinity seawater source (similar to the San Francisco Bay). The total dissolved solids (TDS) concentration of this water source is approximately 30,000 mg/l but varies tidally and seasonally. This source requires more energy and materials to treat than a less-saline brackish groundwater source but less than water taken directly from the ocean.

The desalination plant is based on typical reverse osmosis (RO) system characteristics. Because the RO process has a 50% recovery rate, 20 million gallons per day (MGD) of seawater are extracted to produce 10 MGD, or 10,000 acre-feet annually (AFA), of potable water. Constructing off-site infrastructure necessary to develop the plant site (e.g., roads, sewer, power) is excluded from the analysis.

Supply

The seawater intake is located at the end of a 2000-foot reinforced concrete pier. The pier is supported by 116 concrete piles which are driven into rock, an average 60 feet below the pier deck. Pumps are extended and screened 20 feet below the deck. Four 5-MGD pumps with adjustable frequency drives and necessary electrical and control equipment are installed to obtain the seawater.

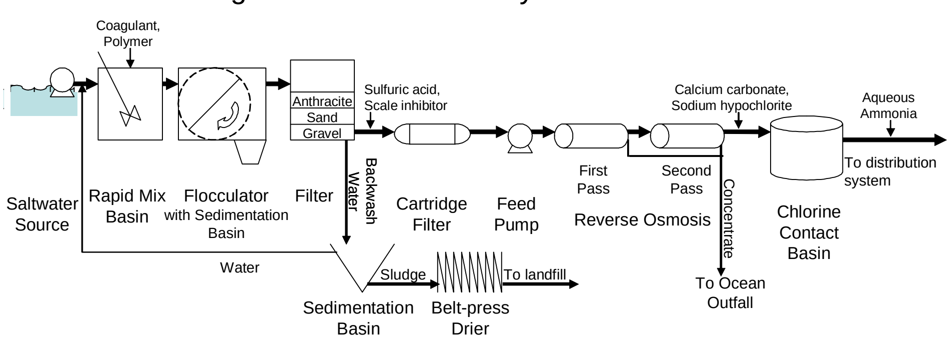
Two 24-inch raw water polyethylene pipelines are attached to the pier to transport water to the plant site. Onshore, the pipes converge into a 30-inch raw water pipeline which carries water one mile to the plant site. Valves, fittings, instrumentation, and electrical service are also included in the assessment.

Electricity necessary to operate the intake pumps and control equipment is included in the operation phase. The maintenance phase includes chemicals used for monthly cleaning of intake and pipelines and replacement parts.

Treatment

Water is desalinated through an RO process. Facilities at the desalination plant include an RO equipment building, an auxiliary building containing an office, laboratory, warehouse, and chemical storage, an outdoor chemical storage area, and a paved driveway and parking lot. The required treatment processes and equipment are illustrated in Figure 6.

Figure 6: Desalination System Schematic



Influent water is "pre-treated" prior to undergoing the RO process. A coagulant and polymer are added to the raw water in the rapid mix basin. The water is then processed through a propeller flocculator and sedimentation basin. The water is then passed through two stages of multimedia filtration (sand and anthracite coal). Sulfuric acid is added to the filtered water to lower the pH. A scale inhibitor is added to complete the pre-treatment process.

Backwashing filters produces waste water which is processed through a gravity settling and thickening process. Sludge from the process is dewatered in a belt-press drier and then transported in dump trucks to a landfill located 20 miles away. About 17 tons (or one truckload) of dewatered sludge will be produced daily.

Pre-treated water is then passed through cartridge filters. High-pressure feed pumps are used to increase the pressure to the required 700 to 1000 psi. The water under pressure enters the two-pass RO system composed of 5 treatment trains. All water is treated in the first pass of the RO process. Approximately half of the water is treated further by the second pass. This design will provide an overall product recovery of 50%; as a result, approximately 10 MGD of concentrated brine must be disposed.

Brine is disposed of through an ocean outfall. A polyethylene pipeline carries the waste water to an ocean outfall where it is diluted with fresh water from another source before being discharged to the bay. Because the brine represents a small proportion of the water discharged through the outfall, construction and operation of the outfall are excluded from the analysis.

Product water from the RO process is post-treated with calcium carbonate to improve taste. Sodium hypochlorite is added and water is stored in a chlorine contact basin to achieve the required disinfection. Aqueous ammonia is added to aid disinfection before the water enters the distribution system. Chemical delivery equipment, piping, instrumentation, control and electrical equipment associated with the treatment plant are also included in the assessment.

Energy use, chemical production, and sludge disposal needed to operate the system are included in the operation phase. The maintenance phase accounts for replacement parts and membrane and filter disposal. Table 1 summarizes assumed chemical use quantities.

Table 1: Chemical Use and Storage

Chemical	**Dosage**	**Annual Consumption**
Coagulant	10 ppm	103,000 gal
Polymer	0.25 ppm	6100 gal
Sulfuric acid	20 ppm	80,000 gal
Scale inhibitor	4 ppm	24,500 gal
Sodium hypochlorite		
As disinfectant	1 ppm	23,500 gal
For maintenance	NA	1800 gal
Calcium carbonate	12 ppm	337,000 lb
Aqua ammonia	0.25 ppm	6000 gal

Distribution

Potable water from the desalination plant is distributed to customers through the same distribution system used for imported water. The infrastructure used for all potable water sources is not included in the assessment. However, because the imported water distribution system is designed to carry water generally from high to low elevations and the desalination plant is located near sea level, the infrastructure to connect the desalination plant to the distribution system is used solely for desalinated water and is considered herein. Ten miles of concrete pipe and two pump stations are installed to make this connection. Valves, fittings, instrumentation, controls, and electrical components are also included in the assessment. The operation phase accounts for energy required to operate the pumps. The maintenance phase includes replacement parts.

Construction Processes

Constructing the desalination system requires the following construction processes: pile-driving, installing pier deck on piles, constructing and completing the intake structure, site clearing and grading, pipeline installation, excavation and compaction for foundation, facility construction, process components installation, and paving and landscaping. Pipeline installation involves trenching, pipe installation, backfilling and compaction, testing, and restoration. Construction is expected to last 15 months. Equipment use during construction to complete these tasks is included in the analysis.

Conclusions

Figure 7 shows results for energy use and GWP. Figure 8 displays results for other air emissions. However, it should be noted that water systems are highly site- and process-specific; general results, such as the relative contribution of the construction, maintenance, and operation phases, may not be applicable to other systems.

Figure 7: Annual Average Energy Use and GWP Results

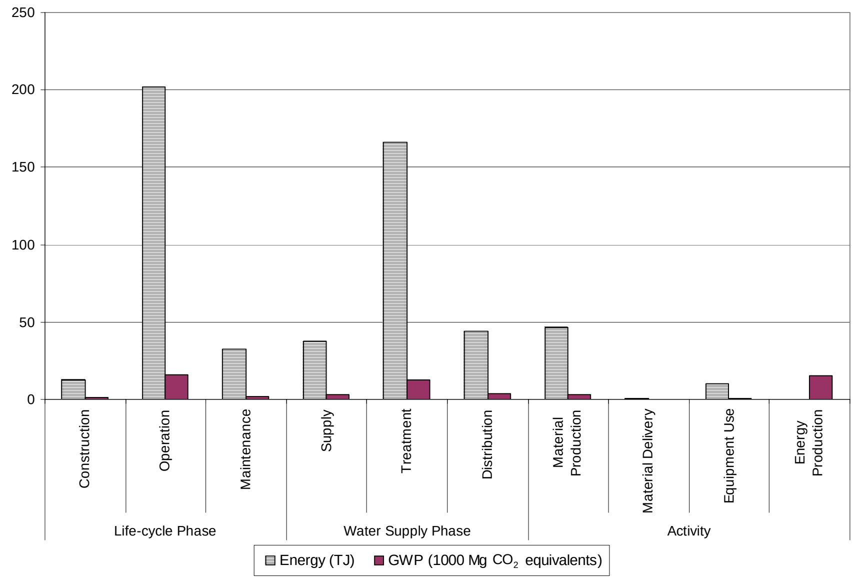
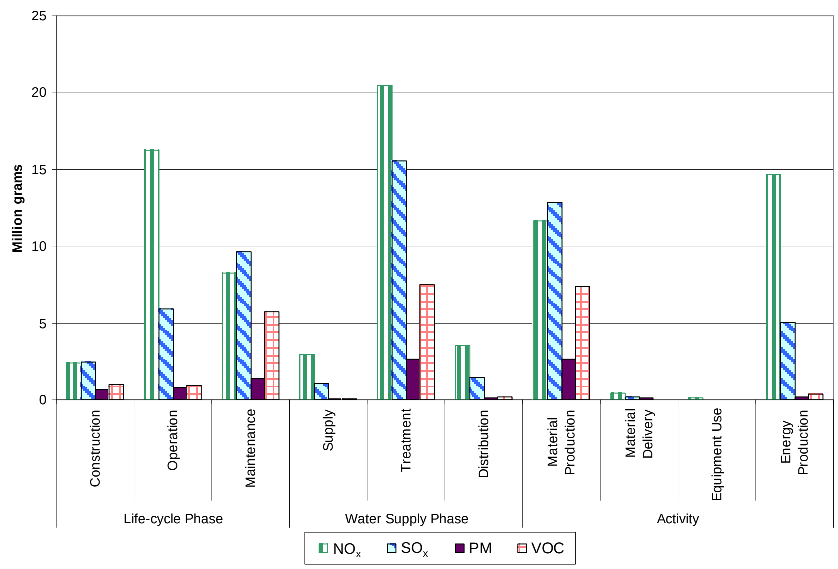


Figure 8: Average Annual Air Emission Results



The results show that the operation phase accounts for the majority of the environmental burden in most categories and dominates energy use and GWP. This result is expected because construction and maintenance occur intermittently but their effects are averaged over the life of the system. However, emissions of PM and VOC in the construction and maintenance phases are significant in spite of averaging effects. The emissions are attributable primarily to material production.

When results are broken down by water supply phase, treatment dominates results in all categories. This result is caused primarily by the electricity-intensive nature of the RO process, but also because treatment is the most complex and material-intensive component of the system.

Energy production contributes most significantly to the GWP, and NO_x categories. For energy use, the effect is an order of magnitude larger than any other activity. Material production is a significant contributor for SO_x, PM, and VOC.

The analysis considered only major components of the system. Incorporation of smaller inputs may affect the final outcome of the results. Accurate estimates of equipment use during construction and maintenance and information on material delivery modes and distances were unavailable. The contribution of these activities is likely underestimated. Future improvements in the analysis will focus on these areas.

The results of this assessment assume that current desalination technology is implemented. As the desalting process continues to improve, particularly in energy efficiency and membrane durability, future technology improvements may change the outcome of the analysis.

Though water supply decisions are unlikely to be made solely on the basis of environmental considerations, incorporating these considerations into the decision-making process is expected to contribute to a more sustainable future. The tool described herein will provide the water industry with a method to assess the environmental effects of the water supply system throughout its life-cycle.

Acknowledgements

The authors would like to acknowledge the support of the National Science Foundation's Graduate Research Fellowship, the University of California Toxic Substances Research and Teaching Program, and the California Energy Commission's Public Interest Energy Research Program.

References

1. Association of California Water Agencies Water Supply Facts Home Page. http://www.acwanet.com/mediazone/waterfacts/view.asp?ID=44 (accessed January 2004).

2. U.S. Department of the Interior Water 2025 Home Page. http://www.doi.gov/water2025/supply.html (accessed January 2004).

3. *Water 2025*. Technical Report. Department of the Interior: Washington, D.C., 2003.

4. van Tilburg, J.; Nieuwlaar, E.; and Geerts, J. in *5th LCA Case Studies Symposium*. SETAC- Europe: Brussels, Belgium, 1997, 213.

5. Crettaz, P.; Jolliet, O.; Cuanillon, J.; and Orlando, S. *Aqua*. 1999, **48**(3), 78-83.

6. Das, T. Clean Technologies and Environmental Policies. 2002, **4**, 32-43.

7. Friedrich, E. *Water Science and Technology*. 2002, **46**(Part 9), 29-36.

8. Herz, R.; Lipkow, A. Water Science and Technology : Water Supply. 2002, **2**(4), 51-72.

9. Emmerson, R.; Morse, G.; Lester, J.; Edge, R. *Water and Environmental Management.* 1995. **9**(3), 317-325.

10. Lundin, M.; Bengtsson, M.; Molander, S. *Environmental Science & Technology*. 2000, **34**(1), 180-186.

11. Roeleveld, P.J.; Klapwijk, A.; Eggels, P.; Rulkens, W. *Water Science and Technology*. 1997, **35**(10), 221-228.

12. Suh, Y.-J.; Rousseaux, P. *Resources, Conservation, and Recycling*. 2002, **35**(3), 191-200.

13. Tillman, A.; Svingby, M.; Lundstrom, H. *International J of LCA*. 1998, **3**(3), 145-157.

14. Cheng, C.L., *Building and Environment*, 2003, **38**(2), 369-379.

15. Watergy: Taking Advantage of Untapped Energy and Water Efficiency Opportunities in Municipal Water Systems. Alliance to Save Energy/ USAID: Washington, D.C., 2002.

16. Curran, M.A. (Ed.) *Environmental Life-Cycle Assessment*. McGraw-Hill: New York, 1996.

17. A Technical Framework for Life Cycle Assessment. in Society of Environmental Toxicology and Chemistry Workshop Report, Smugglers Notch, Vermont, 1991.

18. *Guidelines for Life-Cycle Assessment: A Code of Practice.* Society of Environmental Toxicology and Chemistry: Sesimbra, Portugal, 1993.

19. Environmental Management - Life Cycle Assessment - General Principles and Framework. International Organization for Standardization: Geneva, Switzerland. 1997,

20. Environmental Management - Life Cycle Assessment - Goal and Scope Definition-Inventory Analysis. International Organization for Standardization: Geneva, Switzerland, 1998.

21. International Organization for Standardization, ISO 14000 Home Page, http://www.iso.ch/iso/en/iso9000-14000/iso14000/iso14000index.html (accessed March 2003).

22. Graedel, T.E.; Allenby, B.R. *Industrial Ecology*. 2nd ed. Prentice Hall: Upper Saddle River, N.J., 2003.

23. Ciambrone, D. *Environmental Life Cycle Analysis*. Boca Raton: Lewis Publishers, 1997.

24. Vigon, B.W. *Life-cycle Assessment: Inventory Guidelines and Principles*. Environmental Protection Agency: Cincinnati, Ohio, 1993.

25. Carnegie Mellon University. *Economic Input Output Life Cycle Assessment (EIOLCA).* Green Design Institute. http://www.eiolca.net (Accessed November 2003).

26. Hendrickson, C.; Horvath, A.; Joshi, S.; Lave, L. *Environmental Science & Technology*, 1998, **32**, 184A-191A.

27. *Input-Output Accounts of the U.S. Economy, 1997 Benchmark*. Department of Commerce, Interindustry Economics Division: Washington, D.C., 2002.

28. *National Biennial RCRA Hazardous Waste Report, 1993*. Environmental Protection Agency, Solid Waste and Emergency Response: Washington, D.C., 1995.

29. *1995 Toxics Release Inventory: Public Data Release*. Environmental Protection Agency Office of Pollution Prevention and Toxics: Washington, D.C., 1997.

30. *AirData Database*. Environmental Protection Agency Office of Air and Radiation: Washington, D.C., 2003.

31. Means, R.S. *Heavy Construction Cost Data*, ed. J. Page. 12th ed. Kingston, MA, 1997.

32. Peters, M.S.; Timmerhaus, K.D.; West, R. *Plant Design and Economics for Chemical Engineers*. 5th ed. McGraw-Hill: New York, 2003.

33. American Society of Civil Engineers and American Water Works Association. *Water Treatment Plant Design*. 3rd ed. New York: McGraw-Hill, 1998.

34. Engineering News Record Construction Cost Index Home Page. http://www.enr.com/features/conEco/costIndexes/default.asp (Accessed January 2004).

35. *The Environmental Effects of Freight*. Organization for Economic Cooperation and Development: Paris, 1997.

36. *AP-42 Compilation of Air Pollutant Emission Factors*. Environmental Protection Agency: Washington, D.C., 1995.

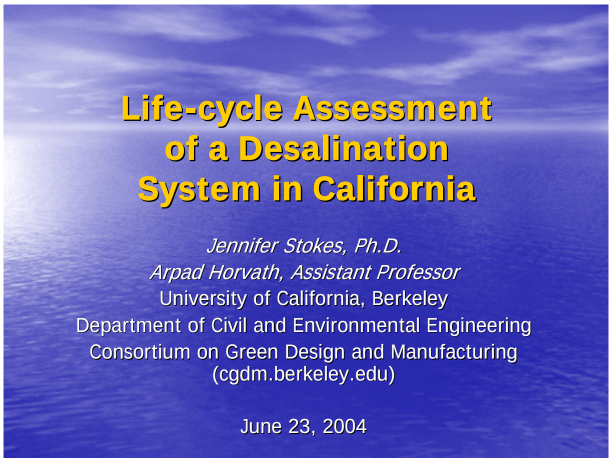
37. Beardsley, M.; Lindhjem, C. *Exhaust Emission Factors for Non-Road Emission Modeling- Compression Ignition*. Environmental Protection Agency: Washington, D.C., 1998.

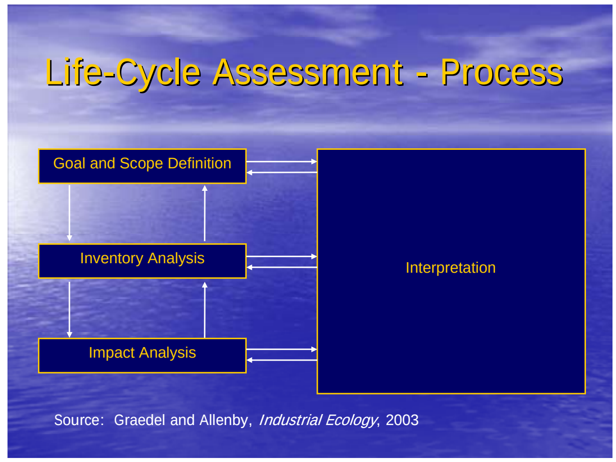
38. Caterpillar Inc. *Caterpillar Performance Handbook*. 27. ed. Peoria, Ill., 1996.

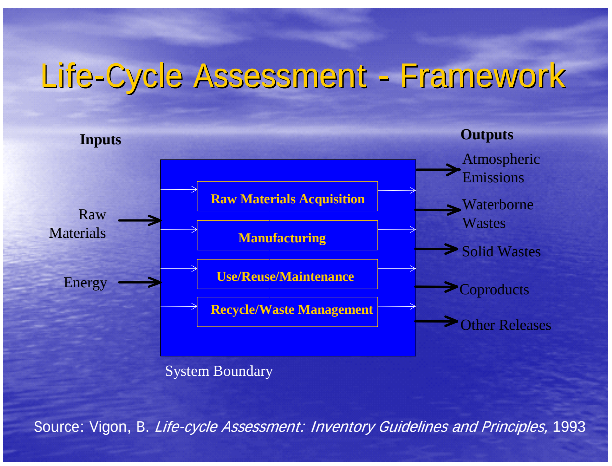
39. The Emissions and Generation Resource Integrated Database (E-GRID2002) Version 1.0, 2000 Data. U.S. Environmental Protection Agency: Washington, D.C., 2002.

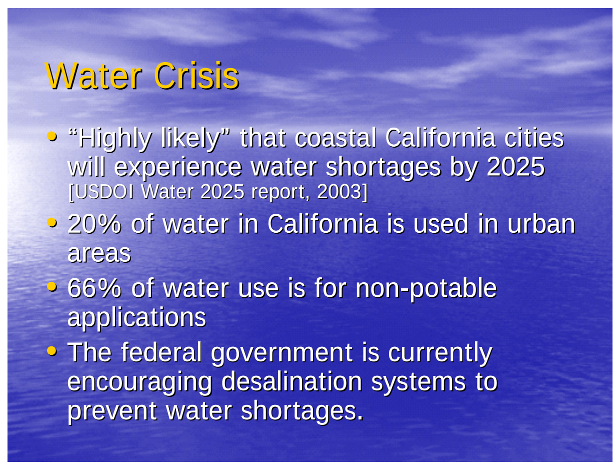
A.3 Presentation at the Air & Waste Management Association (A&WMA) Annual Conference

The following are the slides used to present the subject research at the Air & Waste Management Association Annual Conference in Indianapolis, Indiana, on June 23, 2004.









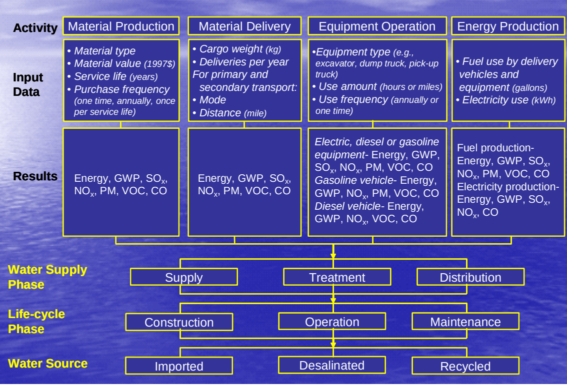
Research Objectives

- To develop an analytical computer-based tool to assist water supply utilities, designers, planners, and policymakers in assessing the environmental effects of their decisions
- To compare water supply alternatives in urban areas of California, especially importing, desalinating, and recycling water

The WEST Tool

- Water-Energy Sustainability Tool
- MS Excel-based *hybrid LCA* model- combining elements of process-based and economic input-output LCA
- Evaluates material production, material delivery, construction processes and equipment use, and energy production
- Provides results for energy use, global warming, and air emissions

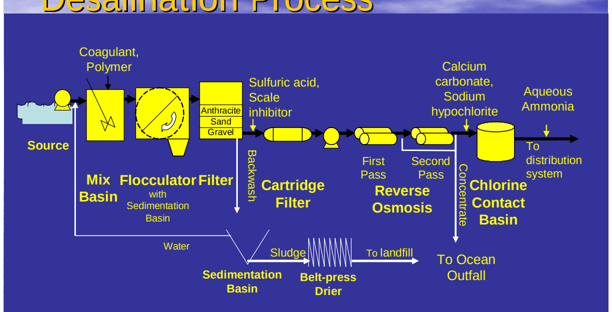
WEST Structure



Desalination System

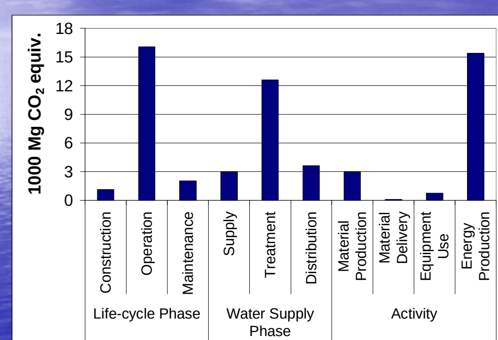
- Located in a hypothetical California city in the San Francisco Bay Area
- Desalination plant produces 10,000 AF of water each year
- Desalination uses reverse osmosis

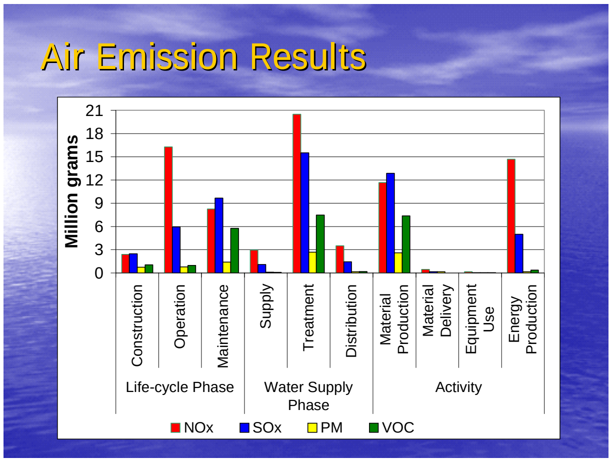
Desalination Process



Source: MMWD 1990

Global Warming Effect Results




Air Emission Results
Million grams
21
18
15
12
9
6
3
0
Construction
Operation
Maintenance
Supply
Treatment
Distribution
Material Production
Material Delivery
Equipment Use
Energy Production
Life-cycle Phase
Water Supply Phase
Activity
NOx
SOx
PM
VOC


Thanks to...
National Science Foundation
University of California Toxic Substances Research and Teaching Program
California Energy Commission Public Interest Energy Research
Questions?

Appendix B. The Water–Energy Sustainability Tool

List of Figures

List of Tables

NOTE: The text in this Appendix is quoted from Dr. Stokes's PhD dissertation [Stokes 2004].

B.1 General Description

In order to quantify air emissions and energy use associated with water systems, the Water-Energy Sustainability Tool (WEST) was created by the author. This tool uses user-defined input data to evaluate emissions and energy use throughout the life-cycle of the system, including construction, operation and maintenance. Decommissioning of the system is not included because sufficient data were not available and it is expected to contribute negligibly to the final result. (One study found that decommissioning contributed less than 1% of the overall environmental burden [Friedrich 2002].)

Figure B,1 describes the structure of WEST analysis.

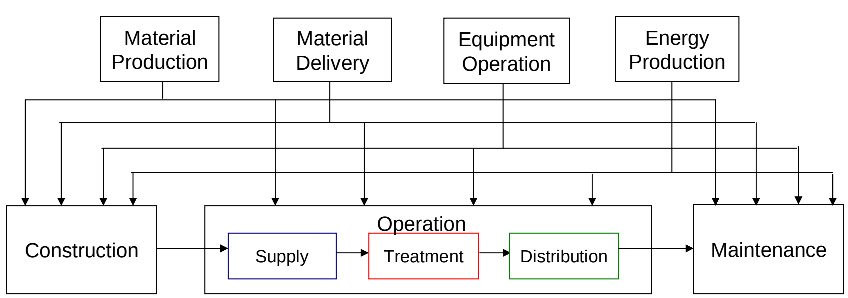


Figure B.1 WEST Tool Structure

As shown in Figure B.1, the tool evaluates energy and material use for four categories of activities: material production, material delivery, equipment use, and energy production. Material production assessment allows the user to inventory the materials used in the system and evaluate the effects of their manufacture or provision throughout the supply chain. Materials considered may include reinforced concrete, pipe, pumps, valves, electrical and control systems, and chemical storage equipment.

The material delivery component assesses the emissions produced and energy used to transport materials to the end-use location by truck, train, ship, or airplane. Equipment use assesses the emissions and fuel use from operating non-transport equipment, especially construction equipment and maintenance vehicles. Energy production focuses on the impact of producing electricity or fuel (e.g., diesel, gasoline, or jet fuel needed for vehicle operation) used in the system.

Each item entered in the tool must be further categorized by the user according to the associated life-cycle phase. An item may be used in the construction, operation, or maintenance phase of the system. These are defined as follows:

Construction includes the facility construction and production, delivery, and installation of equipment present at start-up for the entire system as well as construction equipment operation.

Operation includes all chemicals, non-capital materials (i.e., cartridge and bag filters), and energy used by the system continuously.

Maintenance includes replacement parts for capital equipment (e.g., piping, pumps, membranes, and filter media) and cleaning chemicals for the system.

In addition, each item should be defined as a component of water supply (transporting water from the source to the treatment plant), treatment (ensuring water meets regulatory water quality standards), or distribution (storing water and transporting it to the end-user after treatment). Figure 3.1 provides an illustration of the three different phases of the system.

B.2 Tool Use

The tool created is useful for several audiences, including planners, designers, construction contractors, plant operators, utility administrators and policy analysts. It can be used to evaluate the effects of a variety of water supply decisions, including:

Selecting alternative water supplies (e.g., recycled, imported, or desalinated);

Designing system expansions (e.g., centralized versus distributed treatment);

Changing drinking water standards (i.e., in-plant or point-of-use arsenic removal if a stricter standard is adopted);

Evaluating alternative treatment processes (e.g., membrane versus dual-media filtration, chlorine versus ultraviolet disinfection); and

Choosing materials for infrastructure improvements (e.g., steel versus concrete reservoir, plastic versus iron, steel, or concrete pipe).

Finally, the tool can be used to identify areas where energy efficiency improvements can be focused, material use can be reduced, and environmental burden can be minimized.

B.3 Worksheet Descriptions

The WEST tool is an Excel-based spreadsheet and contains worksheets in four categories: data entry, data, calculations, and results.

B.3.1 Data Entry Worksheets

The data entry pages allow the user to input data related to the analyzed system. Cells in the data entry worksheets are color-coded to reflect their function (e.g., if the cell contains a drop-down list, it is a particular color; a different color if it contains a value which is accessed from a different location in the worksheet; and another if the user can enter any value).

B.3.1.1 Project Definition Worksheets

A general information page requires the user to define the name and location of the water system being analyzed, the population, service area, and customer demographics of the analyzed system, the major facilities in the system (e.g., treatment plants, reservoirs, and large pumping stations), and model parameters (e.g., analysis time-frame and functional unit). Figure B.2 shows the general data entry worksheet. Sample values are shown in the cells.

System Information		
Water System Name	Sample System	
System Location (State)	CA	
Water System Acronym	Samp	
Service area demographics		
Population	100,000	
Size (sq. miles)	50	
Customer demographics		
Residential	60%	%
Single family	80%	%
Multi-family	20%	%
Industrial	20%	%
Commercial	15%	%
Institutional	5%	%
Other	0%	%
Water Sources		
Total (AF/yr, %):	20000	100%
Imported:	10000	50%
Desalinated:	6000	30%
Recycled:	2000	10%
Other:	2000	10%

Model Information	
Analysis Period (yrs)	100
Current year	2004
Functional unit (AF/yr)	100
EIOLCA Base Year	1997
GWE Time Horizon	100

Facility Information								
			Water Sources (%)					
Name	Owned by	Water System Phase	Import	Desalinate	Recycle	Other	Production (AF/yr)	Water to system (%)
Imported Supply	Samp	Supply	100%	0%	0%	0%	10000	100%
Imported Treatment	Samp	Treatment	100%	0%	0%	0%	10000	100%
Desalinated Supply	Samp	Supply	0%	100%	0%	0%	6000	100%
Desalinated Treatment	Samp	Treatment	0%	100%	0%	0%	6000	100%
Recycled Supply	Samp	Supply	0%	0%	100%	0%	2000	100%
Recycled Treatment	Samp	Treatment	0%	0%	100%	0%	2000	100%
Distribution, desalination	Samp	Distribution	0%	100%	0%	0%	6000	100%
Distribution, potable	Samp	Distribution	56%	33%	0%	11%	16000	100%
Distribution, non-potable	Samp	Distribution	0%	0%	100%	0%	2000	100%
	Samp		0%	0%	0%	100%		100%
	Samp		0%	0%	0%	100%		100%

Figure B.2 General Data Entry Worksheet

The general information worksheet also allows the user to divide the components of the system into unique “Facilities” with different parameters such as the volume of water processed (e.g., volume of water transported in a particular aqueduct or volume treated at a particular treatment plant). The facilities table can be seen at the bottom of Figure B.2.

The user also enters data related to construction, transportation, and maintenance equipment used in the system on a separate worksheet. This page allows the user to define the size, model year, engine capacity, productivity, fuel type, and fuel use of various pieces of construction, transportation, or maintenance equipment. For instance, the user can select the excavator model used for construction and the type of dump truck used for sludge disposal during operation. The worksheet contains a variety of pre-defined equipment characteristics but the user can define more precise information if desired. In addition, the user can enter custom equipment parameters. Figure B.3 shows a portion of the equipment input worksheet. The brand or model for each equipment type can be selected from a drop-down menu as shown for the crane.

	Equipment Details							
Activity	**Equipment**	**Brand/Model**	**Engine Capacity**	**Power**	**Productivity**	**Fuel Consumption**	**Fuel Type**	**Emissions Category**
Concrete Placement	Concrete Mix Truck	International 5500i	565 hp		41 ton/h	10.0 gal/h	diesel	DR
	Concrete Pump	Putzmeister 52Z	300 hp			12.0 gal/h	diesel	NR300TO600
	Concrete Vibrator	Oztec GV-5H	6 hp			0.4 gal/h	gasoline	gasoline
	Rebar Cutter	none	NA	NA	NA	NA	NA	NA
	Rebar Bender	none	NA	NA	NA	NA	NA	NA
Excavation and Earthwork	Large Excavator	Caterpillar 375	428 hp			24.7 gal/h	diesel	NR300TO600
	Small Excavator	John Deere 200C	141 hp			9.7 gal/h	diesel	NR100TO175
	Backhoe Loader	none	NA	NA	NA	NA	NA	NA
	Vibratory soil compactor	Dynapac CA 262D	150 hp			9.9 gal/h	diesel	NR100TO175
	Grader	none	NA	NA	NA	NA	NA	NA
	Dozer with ripper	none	NA	NA	NA	NA	NA	NA
	Wheel loader	John Deere 644E	160 hp		4 ton/h	10.6 gal/h	diesel	NR100TO175
	Dump Truck	Sterling L8500	250 hp			13.0 gal/h	diesel	DR
Asphalt Paving	Paver	none	NA	NA	NA	NA	NA	NA
	Pneumatic roller	none	NA	NA	NA	NA	NA	NA
	Tandem roller	none	NA	NA	NA	NA	NA	NA
Meter Reading and Maintenance	Pickup Truck	Average Truck	NA	NA	NA	17 mpg	gasoline	GR
	Automobile	Average Car	NA	NA	NA	30 mpg	gasoline	GR
Sludge Removal	Dump Truck (sludge)	GMC c8500	275 hp			13.0 gal/h	diesel	DR
	Wheel loader (sludge)	John Deere 624E	135 hp		3 ton/h	9.3 gal/h	diesel	NR100TO175
General Equipment	Generator	none	NA	NA	NA	NA	NA	NA
	Air Compressor	none	NA	NA	NA	NA	NA	NA
	Crane	Grove TMS 900E	450 hp		90 ton/h	25.0 gal/h	diesel	NR300TO600
	Cutting torch		NA	NA	NA	NA	NA	NA
	Forklift		NA	NA	NA	NA	NA	NA
	Power saw		NA	NA	NA	NA	NA	NA
	Welder		NA	NA	NA	NA	NA	NA
	Tanker Truck		NA	NA	NA	NA	NA	NA
	Pedestal Boom	none	NA	NA	NA	NA	NA	NA
Custom	Plate Compactor IngRand BXR6(	Robin EY15	4 hp	NA	4200 tons/hr	0.3	gasoline	gasoline
	Custom 2	Edit	Edit	Edit	Edit	Edit	Edit	Edit
	Custom 12	Edit	Edit	Edit	Edit	Edit	Edit	Edit

Grove RT525E
Grove TMS700E
Terex ATT 600 (60 ton)
Terex ATT 900
Grove TMS 900E
Custom
none

References for equipment data are located in the "Equipment Pool" worksheet.

Diesel Road Equipment Assumptions	
Model Year	1998-2000
Cumulative Miles	70000

Diesel Non-road Equipment Assumptions	
Model Year	2000

Entry-Project Info | **Entry-Equipment** | Entry- Material Production | Entry-Material Delivery | Entry-Equipment Use | Entry-Er

Figure B.3 Equipment Data Entry Worksheet

The small tables at the bottom of the worksheet allow the user to specify the model year and cumulative miles for all diesel road equipment as well as the model year for diesel, non-road vehicles (i.e., construction equipment).

B.3.1.2 Activity Entry Worksheets

A separate data entry page is available for each of the four included activities – material production, material delivery, equipment use, and energy production. These are discussed in these sections.

To simplify data management by the user, material production and delivery data are entered on the same worksheet, shown in Figure B.4. Columns are numbered in parentheses above the column headings for reference.

General			Material		Cost					Transportation					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Lifecycle Phase	Facility	Description	Material	Service Life (years)	Unit Cost $	Units	Units (#)	Pay Schedule	Year of Pur-chase	Cargo mass (kg)	Annual Delivery (#/year)	Primary Transport Mode	Distance (miles)	Secondary Transport Mode	Distance (miles)
Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions	Instructions
Construction	Desalinated Supply	Concrete	Concrete, ready-mixed	100	$ 56	per cubic yard	8000	once per service life	2002	12247200	0.01	none	20		
Construction	Desalinated Supply	Steel Pipe	Pipe, steel	75	$ 68,000	total	1	once per service life	2001	150000	0.01	Local Truck	50		
Construction	Desalinated Treatment	RO membranes	Cellulose acetate	6	$ 415	each	200	once per service life	2000	20000	0.17	Long-distance Truck	500		
Construction	Desalinated Treatment	Filter media	Anthracite	10	$ 1,500	total	1	once per service life	2000	15000	0.10	Train	3000	Local Truck	50
Operation	Desalinated Treatment	Chemicals	Chemicals, industrial	1	$ 300,000	total	1	once per service life	2002	50000	1.00	Local Truck	30		
Construction	Distribution, desalination	Pipe	Pipe, plastic	60	$ 40,000	total	1	once per service life	2002	30000	0.02	Local Truck	50		
Construction	Imported Supply	Concrete	Concrete, ready-mixed	100	$ 56	per cubic yard	90000	once per service life	2002	5000000	0.01	none	20		
Operation	Imported Treatment	Chemicals	Chemicals, industrial	1	$ 200,000	total	1	once per service life	2002	30000	1.00	Local Truck	30		
Construction	Recycled Supply	Pipe	Pipe, plastic	60	$ 78,000	total	1	once per service life	2002	25000	0.02	Local Truck	50		
Construction	Recycled Treatment	Pumps	pumps	30	$ 15,000	total	1	once per service life	2002	3000	0.03	Long-distance Truck	100		
Operation	Recycled Treatment	Chemicals	Chemicals, industrial	1	$ 3,000	total	1	once per service life	2002	5000	1.00	Local Truck	30		
Construction	Distribution, potable	Pipe	Pipe, ductile iron	75	$ 150,000	total	1	once per service life	2002	1000000	0.01	Local Truck	50		
Construction	Distribution, non-potable	Pipe	Pipe, plastic	60	$ 40,000	total	1	once per service life	2002	10000	0.02	Local Truck	50		

Figure B.4 Material Production and Delivery Entry Worksheet

The first two columns allow the user to select the life-cycle phase (construction, operation, or maintenance) and facility (as defined in the Facility Table shown in Figure B.2) from drop-down menus. The third column allows the user to describe the material being evaluated. Column 4, labeled "Material," allows the user to select the appropriate material from a predefined list of materials. The default service life for that material is automatically added to the fifth column, “Service Life,” but may be edited by the user.

Cost information is entered in columns 6 – 10. The unit cost is entered in column 6 and the units are defined in column 7 (e.g., cost per foot, cost per cubic yard, cost per unit, or total cost). In column 8, the number of units required is entered. Column 9 allows the user to select the pay schedule from a drop-down menu. The pay schedule choices are either: “one time” for purchases which are made once in the analysis period (e.g., forms for concrete construction), “once per service life” for purchases that are made whenever the equipment reaches the end of its life (e.g., pumps and RO membranes), or “annually” for purchases which are made continuously. If “annually” is chosen, the units of items purchased should be equivalent to those used in an average year. Column 10 allows the user to define what year the purchase was made or the year for which the costs are reported (e.g., 2000 dollars) so that costs can be adjusted to the EIO-LCA model year.

Columns 11 – 16 allow the user to enter parameters relevant for material delivery. The user enters cargo weight (column 11). The annual deliveries made (column 12) is calculated automatically based on the pay schedule, the service life and the analysis timeframe. The primary mode of transportation (i.e., truck, train, ship, or airplane) and distance traveled are entered in Columns 12 and 13, respectively. If necessary, a secondary transport mode as well as the distance traveled can be entered in Columns 15 and 16, respectively.

The equipment use entry worksheet is shown in Figure B.5. Columns are numbered above the table headings. The values shown are for demonstration purposes only.

General			Equipment				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Life Cycle Phase	Facility	Description	Activity	Vehicle Type	Amount of Use		Frequency of Use
Construction	Desalinated Supply	Excavation for pipeline	Excavation and Earthwork	Large Excavator	200	Hours Used	one time
Operation	Desalinated Treatment	Sludge disposal	Sludge Removal	Dump Truck (sludge)	15500	Miles Driven	annually
Construction	Imported Treatment	Concrete delivery for plant	Concrete Placement	Concrete Mix Truck	35000	Miles Driven	one time
Construction	Recycled Treatment	Crane for tank placement	General Equipment	Crane	12	Hours Used	one time
Construction	Distribution, potable	Crane for pipe placement	General Equipment	Crane	100	Hours Used	one time
Construction	Recycled Treatment	Plant parking	Asphalt Paving	Paver	20	Hours Used	one time
Operation	Distribution, potable	Meter reading	Meter Reading and Maintenance	Pickup Truck	20000	Miles Driven	annually
						Hours Used	
						Hours Used	

Figure B.5 Equipment Use Entry Worksheet

For equipment use, the user selects the life-cycle phase and facility from drop-down menus in Columns 1 and 2, respectively. The user may enter a description in Column 3. Column 4 provides a drop-down menu that allows the user to define the category of equipment they are considering. The choices are defined in the first column of the Equipment Entry worksheet and can be seen in Figure B.3. The category choices are: Excavation and Earthwork, Concrete Placement, Asphalt Paving, Sludge Disposal, Meter Reading and Maintenance, General, and Custom.

Once the equipment category has been selected, the user may select the type of equipment from a drop-down menu containing equipment associated with the activity category in Column 5. Figure B.3 also shows what types of equipment are available for each activity in the second column.

The user must also enter the number of hours used or miles driven by the relevant piece of equipment in column 6. Column 7 automatically tells the user which units (hours or miles) should be entered depending on the piece of equipment selected. Column 8 allows the user to define the frequency of use for the equipment using choices from a drop down menu. The user can select either “one time” or “annually.”

The energy production data entry sheet is shown in Figure B.6. Electricity use data is entered into this form. Energy production also includes production of fuel used to operate delivery vehicles and equipment. Fuel use is calculated automatically based on data entered on the material delivery and equipment use entry worksheets.

(1) Lifecycle Phase	(2) Facility	(3) Description/Model	Electricity Use (4) Amount (kWh)	(5) Frequency	(6) Total kWh Used
Operation	Imported Supply	Electricity	2000	per acre-foot	20000000
Operation	Desalinated Treatment	Electricity	400000	per year	400000
Operation	Distribution, potable	Electricity	1150000	per year	1150000
Operation	Distribution, non-potable	Electricity	400	per acre-foot	800000
Operation	Imported Treatment	Electricity	150000	per year	150000

Figure B.6 Energy Production Entry Worksheet

Columns 1, 2 ,and 3 work much as they did for the other data entry worksheets. The first two columns contain drop-down menus. Column 4 allows the user to enter the amount of electricity (in kilowatt-hours [kWh]) required to operate the system. The units associated with that value are selected from a drop-down menu in column 4. Electricity may be entered in terms of kWh per AF or kWh per year. The amount of electricity used annually is calculated automatically in column 6.

B.3.2 Calculations

Calculation pages combine user-entered information and standard data to determine energy use and air emissions for all categories. The following sections discuss the general calculations for each of the four activities considered.

B.3.2.1 Material Production

The material production effects are estimated using emission factors obtained from the EIO-LCA model [CMU 2004]. Each material available in the drop-down menu in column 4 of the Material Production Entry worksheet (Figure B.4) is associated with an economic sector included in EIO-LCA model. Table B.1 provides a representative list of common components of a water system and their associated EIO-LCA sectors. The default service life for each material type is also listed. The emission factors associated with each EIO-LCA sector are included in Appendix D.1.1.

Material Choices	EIO sector	Life (yr)	Distance
Acid, activated carbon, alkali, alum, caustic soda, ammonium and chlorine compounds	Industrial inorganic & organic chemicals	1	30
Adhesives	Adhesives and sealants	3	15
Adjustable frequency drives and controls	Relays and industrial controls	15	500
Aggregate, sand, and gravel	Sand and gravel	100	40
Anthracite	Coal	10	3000
Asphalt	Asphalt paving mixtures and blocks	20	20
Blowers and fans	Blowers and fans	30	500
Brick	Brick and structural clay tile	50	15
Cartridge and bag filters and RO membranes	Celluosic manmade fibers	6	75
Compressors	Pumps and compressors	30	500
Concrete block	Concrete block and brick	75	30
Concrete pipe and precast concrete	Concrete products, except block	75	30
Concrete, ready-mixed	Ready-mixed concrete	20	100
Electrical equipment	Electrical industrial apparatus, n.e.c.	15	500
Flowmeters	Measuring and metering devices	15	250
Generators and motors	Motors and generators	30	500
Industrial equipment	General industrial machinery and equipment, n.e.c.	15	500
Ion exchange resins	Plastic materials and resins	5	1000
Iron and steel forgings	Iron and steel forgings	75	50
Laboratory equipment	Lab apparatus and furniture	15	150
Landscaping	Landscape and horticultural services	40	25
Lime	Lime	1	30
Petroleum products (gasoline, diesel)	Petroleum refining	1	10
Pipe, cast and ductile iron or steel	Metal pipe, valves, and fittings	75	50
Pipe, plastic	Misc plastic products, n.e.c.	60	50
Polymers	Manmade organic fibers, except cellulosic	1	50
Pumps	Pumps and compressors	30	500
Pumps, metering	Measuring and dispensing pumps	15	150
Reinforcing steel	Blast furnaces & steel mills	100	40
Tanks, redwood	Sawmills & planing mills, general	40	50
Tanks, steel	Iron and steel forgings	75	500
Turbines	Turbine and turbine generator sets	30	500
Valves and fittings, metal	Metal pipe, valves, and fittings	20	50
Valves and fittings, plastic	Misc plastic products, n.e.c.	15	30
Water treatment and desalting chemicals	Chemicals and chem. preparations, n.e.c.	1	30
Wood	Sawmills & planing mills, general	40	25

Table B.1 Material Details

Costs are adjusted to determine the life-cycle cost (LCC) associated with each material through the entire analysis period. In addition, if necessary costs are adjusted to 1997 dollars using the *Engineering News Record's Construction Cost Index* (CCI) [Peters 2003; ENR 2004]. The CCI values are provided in Appendix D.1.2.

Once the life-cycle cost of the material is determined, the environmental effects are determined using the following equation:

Equation B.1: $$Emissions_i = \sum_{k=1}^{n}\sum_{j=1}^{n} \frac{EF_{ij} * LCC(1997\$) * FunctUnit}{Annual\ Production_k * AnalysisTimeFrame}$$

Where i = the environmental effect considered;
j = the material considered;
k = the facility considered;
EF = the emission factor determined by EIO-LCA for the given chemical and material;
LCC(1997$) = the total cost of the material over the analysis period in 1997 dollars;
FunctUnit = the functional unit defined on the Project Entry worksheet;
Annual Production = the annual volume of water processed (AF) for the facility; and
AnalysisTimeFrame = the analysis period defined on the Project Entry worksheet.

In addition, factors are used to allocate the result to the correct life-cycle phase, water supply phase (based on the facility chosen) and proportionally to the water produced associated with each water source. In addition, the result is adjusted to account for the proportion of water produced by the facility which is sold to the system being considered (i.e., if only half of the water produced at the facility is used by the system under evaluation, then half of the material costs are allocated as well). Finally, the results are allocated so the first material purchase is assigned to the construction phase and additional purchases are assigned to the maintenance phase.

B.3.2.2 Material Delivery

Material delivery emissions are a function of delivery distance and frequency, cargo mass, and mode of transportation. Material delivery by truck, rail, ship, and airplane can be evaluated by the WEST tool. Transport vehicle emission factors are from [OECD 1997; Romano 1999; Sorenson 1995; EEA 2002; ATA 2001; IPCC 1999] and are provided in Appendix D.1.3. Equation B.2 provides the general equation used to calculate delivery emissions.

Equation B.2:

$$Emissions_i = \sum_{l=1}^{2}\sum_{k=1}^{n}\sum_{j=1}^{n} \frac{EF_l * AnnualDeliveries_j * CargoMass_j * Distance_{jkl} * FunctUnit}{Annual\ Production_k * AnalysisTimeFrame}$$

Where i = the environmental effect considered;
j = the material considered;
k = the facility considered;
l = the mode of transportation considered (primary or secondary);
EF = the emission factor for the mode of transport;
Annual Deliveries = the number of deliveries which occur in the average year (calculated on the material Production Entry worksheet);
CargoMass = the mass (in kg) of material *j* transported each year;
Distance = the transport distance (in miles) for the material and mode of transport;
FunctUnit = the functional unit defined on the Project Entry worksheet;
Annual Production = the annual volume of water processed (AF) for the facility; and
AnalysisTimeFrame = the analysis period defined on the Project Entry worksheet.

Calculations for air transport are more complicated, involving different emission factors for take-off and landing cycles and cruising flight. The result may also be adjusted to account for the percent of water produced at each facility which is used by the system under evaluation. Energy use is calculated based on expected fuel consumption and the energy content of the fuel (gasoline, diesel, or jet fuel).

B.3.2.3 Equipment Use

Equipment emissions are a function of model year, equipment type, motor capacity, and amount of use. Sources for emissions factors are as follows: diesel road vehicles [EPA 1995], diesel non-road vehicles and equipment [CARB 2002; EPA 1998], gasoline vehicles and equipment [EPA 1996], and electric equipment [E-GRID 2002]. The emissions factors are provided in Appendix D.1.4. Calculations vary somewhat depending on the type of equipment but the general equation used to calculate emissions is provided in Equation B.3. Equipment data is from a variety of sources (e.g., [Caterpillar 1996]; [John Deere 2004]) and is provided in Appendix D.2.

Equation B.3: $$Emissions_i = \sum_{k=1}^{n} \sum_{m=1}^{n} \frac{EF_{im} * Use * EngineCapacity * FunctUnit}{Annual\ Production_k * AnalysisTimeFrame}$$

Where i = the environmental effect considered;
k = the facility considered;
m = the equipment considered;
EF = the emission factor determined for the given equipment and effect;
Use = the amount of use (in hours or miles, depending on equipment type);
EngineCapacity = motor capacity (in horsepower or kW) for the given equipment;
FunctUnit = the functional unit defined on the Project Entry worksheet;
Annual Production = the annual volume of water processed (AF) for the facility; and
AnalysisTimeFrame = the analysis period defined on the Project Entry worksheet.

Calculations for diesel road emissions are also include factors that account for vehicle deterioration (i.e., emission increase as the vehicle ages).

B.3.2.4 Energy Production

Energy production includes emissions due to refining fuel for use in delivery vehicles and construction equipment and caused by electricity generation. Fuel production emissions are evaluated using emission factors from EIO-LCA [CMU 2004]. The environmental effect is calculated as shown in Equation B.1.

Electricity generation emission factors were obtained from EPA's E-GRID model [E-GRID 2002]. Emission factors are listed in Appendix D.1.5. The emission factors are specific to the energy mix for California and are available for any U.S. state. Emissions were estimated using Equation B.4.

Equation B.4: $$Emissions_i = \sum_{k=1}^{n} \frac{EF_i * AnnualElectricityUse_k * FunctUnit}{Annual\ Production_k}$$

Where i = the environmental effect considered;
k = the facility considered;
EF = the emission factor found in E-GRID for the given chemical;
AnnualElectricityUse = the annual electricity use (kWh) for the facility; and
FunctUnit = the functional unit defined on the Project Entry worksheet;
Annual Production = the annual volume of water processed (AF) for the facility.

B.3.3 Results

Results are then displayed both numerically and graphically on the results pages. Results are broken down to display information according to life-cycle phase (construction, operation, and maintenance), water supply phase (supply, treatment, and distribution), and activity category (material production, material delivery, equipment use, and energy production). Energy use, GWP, and air emissions (NO_x, PM, SO_x, VOC, and CO) are reported in terms of average annual emissions per functional unit of output. A sample results page is presented in Figure B.7. Figure B.7 is intended to show how results are presented in the WEST tool rather than to provide meaningful results.

Results Explanation:
In the table at right, and the first row of graphs, the results are broken down by three different criteria (life-cycle phase, water supply phase, and water source). The table below and bottom two rows of graphs show the results broken down specifically into the 27 possible categories. Refer to the key to abbreviations at right to decode the category code.

Contaminant	Life-cycle Phase			Water Supply Phase			Water Source		
	C	O	M	S	T	Di	I	D	R
Energy	#####	#####	#####	8.E+02	4.E+03	2.E+03	#####	#####	#####
CO_2 eq.	#####	#####	#####	7.E+01	3.E+02	1.E+02	#####	#####	#####
NO_x	9.E-02	3.E-01	5.E-01	7.E-02	6.E-01	2.E-01	1.E-01	6.E-01	1.E-01
PM	2.E-02	1.E-02	1.E-01	2.E-03	9.E-02	4.E-02	2.E-02	9.E-02	2.E-02
SO_x	9.E-02	1.E-01	6.E-01	3.E-02	5.E-01	2.E-01	1.E-01	6.E-01	8.E-02
VOC	3.E-02	2.E-02	3.E-01	2.E-03	3.E-01	4.E-02	2.E-02	3.E-01	2.E-02
CO	1.E-01	3.E-01	4.E-01	7.E-02	4.E-01	3.E-01	2.E-01	5.E-01	1.E-01

* VOC category sums VOC, NMVOC, and HC results from other pages for simplicity.

Key to Abbreviations

Life-cycle Phase		Water Supply Phase		Water Source	
C	Construction	S	Supply	I	Imported
O	Operation	T	Treatment	D	Desalinated
M	Maintenance	Di	Distribution	R	Recycled
Contaminants				**Units**	
CO_2 eq.	Carbon dioxide equivalents	NMVOC	Non-methane volatile organic compounds	Mg	Million grams
NO_x	Nitrogen oxides	VOC	Volatile organic compounds	GJ	Gigajoules
PM	Particulate matter	CO	Carbon monoxide		
SO_x	Sulfur oxides	HC	Hydrocarbons		

Emissions (Mg, except energy in GJ))

Contaminant	Construction: Supply I	Supply D	Supply R	Treatment I	Treatment D	Treatment R	Distribution I	Distribution D	Distribution R
Energy	#####	#####	#####	8.E-01	#####	#####	#####	#####	5.E+01
CO_2 eq.	4.E-01	7.E-01	1.E-01	6.E-02	#####	#####	#####	#####	3.E+00
NO_x	2.E-03	3.E-03	4.E-04	5.E-04	2.E-02	9.E-03	2.E-02	2.E-02	2.E-02
PM	3.E-04	6.E-04	8.E-05	7.E-05	4.E-03	2.E-03	4.E-03	5.E-03	3.E-03
SO_x	1.E-03	3.E-03	4.E-04	2.E-04	2.E-02	5.E-03	2.E-02	2.E-02	1.E-02
VOC	4.E-04	7.E-04	1.E-04	1.E-04	1.E-02	2.E-03	5.E-03	5.E-03	4.E-03
CO	2.E-03	4.E-03	7.E-04	3.E-04	1.E-02	7.E-03	3.E-02	3.E-02	2.E-02

Contaminant	Operation: Supply I	Supply D	Supply R	Treatment I	Treatment D	Treatment R	Distribution I	Distribution D	Distribution R
Energy	4.E+02	2.E+02	#####	#####	#####	#####	6.E+01	#####	#####
CO_2 eq.	3.E+01	1.E+01	#####	8.E-01	#####	#####	5.E+00	#####	#####
NO_x	3.E-02	1.E-02	1.E-02	3.E-03	2.E-01	2.E-02	5.E-03	1.E-02	5.E-02
PM				5.E-04	1.E-02	2.E-03			
SO_x	9.E-03	4.E-03	4.E-03	2.E-03	7.E-02	1.E-02	1.E-03	3.E-03	1.E-02
VOC				1.E-03	1.E-02	5.E-03			
CO	3.E-02	1.E-02	1.E-02	2.E-03	2.E-01	2.E-02	4.E-03	1.E-02	4.E-02

Contaminant	Maintenance: Supply I	Supply D	Supply R	Treatment I	Treatment D	Treatment R	Distribution I	Distribution D	Distribution R
Energy	#####	#####	3.E+00	3.E-01	1.E+03	#####	#####	#####	#####
CO_2 eq.	2.E-01	6.E-01	2.E-01	2.E-02	9.E+01	#####	#####	#####	#####
NO_x	7.E-04	3.E-03	7.E-04	9.E-05	3.E-01	3.E-02	5.E-02	5.E-02	7.E-03
PM	2.E-04	5.E-04	1.E-04	2.E-05	6.E-02	1.E-02	1.E-02	1.E-02	1.E-03
SO_x	8.E-04	2.E-03	8.E-04	9.E-05	4.E-01	2.E-02	6.E-02	7.E-02	7.E-03
VOC	2.E-04	7.E-04	2.E-04	2.E-05	2.E-01	4.E-03	1.E-02	1.E-02	2.E-03
CO	1.E-03	4.E-03	1.E-03	1.E-04	2.E-01	2.E-02	9.E-02	1.E-01	1.E-02

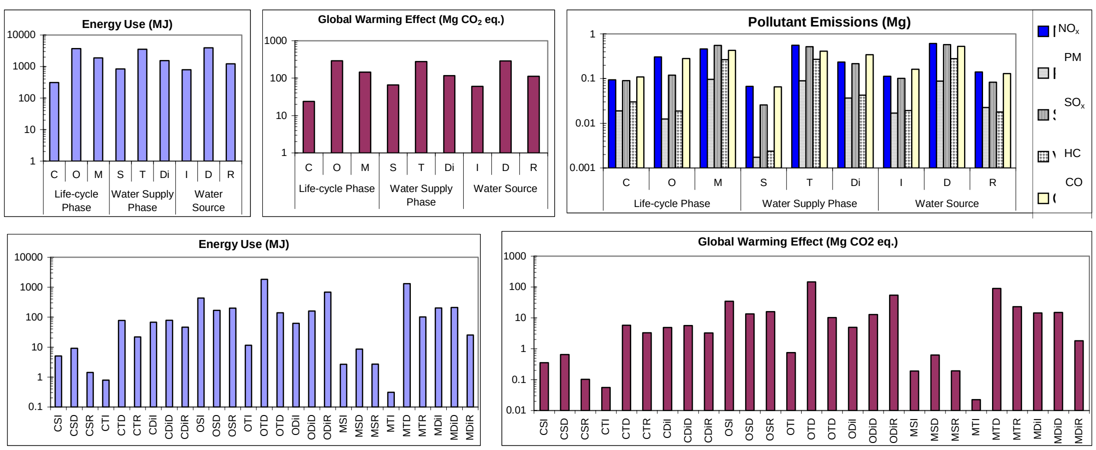


Figure B.7 Sample Results Worksheet

In addition to emission mass or energy use, results can be reported in terms of external costs or by material use as described in the following.

B.3.3.1 External Cost

Environmental valuations for air emissions (CO_2 eq., NO_x, PM, SO_x, VOC, and CO) were obtained from available literature [Matthews 2000]. These values are included in Appendix D.1.6. The environmental valuations attempt to capture externalities (e.g., environmental damage, health effects) by translating each unit of chemical emission into a monetized value. The monetized vales can then be compared between the different chemicals.

The external costs estimates obtained from Matthews were adjusted from 1992 dollars to 1997 dollars using the 7% discount rate suggested by the Office of Management and Budget [OMB 1992]. The WEST model evaluates the external costs associated with each chemical in 1997 dollars and reports the results both graphically and numerically.

B.3.3.2 Material Use

Material production and material delivery results can be reported on the basis of the use of the material. Each component is classified into one of six different material use categories – construction materials, piping, chemicals, equipment, fuel, and other. These classifications can be used to determine the relative contribution of materials in each category to the overall environmental effects. Table B.2 provides a partial list of materials included in the WEST model and their assigned material use categories.

Material Choices	**Material Use**
Acid, alkali, alum, caustic soda, ammonium and chlorine compounds	Chemicals
Adhesives	Other
Adjustable frequency drives and controls	Equipment
Aggregate, sand, and gravel	Equipment[1]
Anthracite	Equipment
Asphalt	Construction
Blowers and fans	Equipment
Brick	Construction
Cartridge and bag filters and RO membranes	Equipment
Compressors	Equipment
Concrete block nd precast concrete	Construction
Concrete pipe	Piping
Concrete, ready-mixed	Construction
Electrical equipment	Equipment
Flowmeters	Equipment
Generators and motors	Equipment
Industrial equipment	Equipment
Ion exchange resins	Equipment
Iron and steel forgings	Varies
Laboratory equipment	Equipment
Landscaping	Other
Lime	Chemical
Petroleum products (gasoline, diesel)	Fuel
Pipe, cast and ductile iron or steel	Piping
Pipe, plastic	Piping
Polymers	Chemicals
Pumps	Equipment
Pumps, metering	Equipment
Reinforcing steel	Construction
Tanks, redwood	Equipment
Tanks, steel	Equipment
Turbines	Equipment
Valves and fittings, metal	Piping
Valves and fittings, plastic	Piping
Water treatment and desalting chemicals	Chemicals
Wood	Construction

Notes:
(1) Aggregate is classified as equipment if it is used as filter media.

Table B.2 Material Use Classification

B.4 Material and Equipment Use Estimation

A separate Excel-based spreadsheet was created which evaluates the materials and equipment needed to construct the common components of a water system. This data analysis companion tool, called WEST-DA, is described in the following sections.

B.4.1 Material Use Estimation

Estimates of material use can be made for common components of water systems using the WEST-DA. For supply and distribution systems, common components include dams, reservoirs, pump stations, storage tanks, wells, pipelines, canals, conduits, tunnels, fittings, valves, and valve boxes. For treatment plants, common components include office and administrative buildings, chemical storage areas, warehouses, process equipment and facilities (e.g., filters, flocculators, disinfectant contact chambers), pumps, and tanks.

The WEST-DA tool estimates the volume of concrete and steel needed to construct reinforced concrete facilities based on their dimensions. The tool uses a default assumption that reinforced concrete is 2% steel by volume. An average wall thickness can be defined in the tool; the default value is 1 ft. Forms used for cast-in-place concrete are estimated. A parameter can be defined which sets the average number of times forms will be reused before disposal. The default value is 3.

Cost information for common components is available in the WEST-DA tool. Costs for pipe, pumps, fittings, valves, flowmeters, filter media, chemicals, precast concrete valve boxes, steel and wood tanks, and wells are included. The cost data is included in Appendix D.3. Most cost information is from *Means Cost Estimating Guide* [Means 1997] or *Plant Design and Economics for Chemical Engineers* [Peters 2003].

When cost information is not available for a particular equipment size (e.g., pipe diameter, pump motor capacity, or tank storage volume), the costs are estimated in one of two ways. If cost information is available for larger and smaller equipment, the value is interpolated. If such information is not available, the cost is estimated using Equation B.5 [Peters 2003].

Equation B.5: $CostA = CostB * (\frac{SizeA}{SizeB})^{0.6}$

In this equation, Cost B is a known cost for piece of equipment which is similar except for size. Size should be the dimension on which price is primarily based (e.g., pipe diameter). The exponent of 0.6 is used for all equipment with the following exceptions: for tanks, the exponent is 0.57 and for pumps it is 0.34.

For all infrastructure, electrical equipment and instrumentation costs were estimated using factors which are appropriate for simple fluid processing plants [Peters 2003]. For treatment plants, factors were also used to estimate landscaping costs. In addition, the tool automatically calculates the weight of pipe, valves, fittings, steel, concrete, and filter media based on their unit weights. The weight can then be entered in to the material delivery section of the WEST tool.

B.4.2 Equipment Use Estimation

Equipment use was also estimated using the WEST-DA spreadsheet. The WEST-DA tool allows the user to input the following site-specific parameters (default values are listed in parentheses): compaction lift height (0.5 ft.), excavated soil expansion factor (80%), round-trip off-haul distance for excess soil (60 miles), average on-site haul distance for sitework (300 ft.), round-trip concrete delivery distance (40 miles), and average excess excavation beyond the necessary boundaries (1 ft. below and 4 ft. on each side for foundations, none on the sides for trenching). General construction parameters are provided in

Appendix D.4. Equipment productivity values were based on manufacturer's information for the specific equipment or general industry data [Means 1997] and are listed in Appendix D.5.

B.5 References

[ATA 2001]. *Annual Report 2001*. Air Transport Association, http://www.airlines.org/econ/files/2001AnnualReport.pdf (Accessed April 27, 2004.)

[CARB 2002]. "Off-Road Emissions Model; Mailout MSC #99-32." California Air Resources Board. http://www.arb.ca.gov/msei/msei.html. Accessed May 1, 2002.

[Caterpillar 1996]. Caterpillar, Inc. *Caterpillar Performance Handbook*. 27th ed. Peoria, Ill., 1996.

[CMU 2004]. "Economic Input-Output Life-cycle Assessment (EIO-LCA)." home page. Carnegie Mellon University Green Design Initiative. http://www.eiolca.net. (Accessed March 23, 2004.)

[E-GRID 2002]. *The Emissions and Generation Resource Integrated Database (E-GRID2002) Version 1.0, 2000 Data*. U.S. Environmental Protection Agency: Washington, D.C., 2002.

[EEA 2002]. *EMEP/CORINAIR Emission Inventory Guidebook - 3rd edition*. 2002, European Environmental Agency. http://reports.eea.eu.int/EMEPCORINAIR3/en (Accessed April 27, 2004.)

[ENR 2004]. "Construction Cost Index" home page. Engineering News Record. http://www.enr.com/features/conEco/costIndexes/default.asp (Accessed January 2004).

[EPA 1995]. "Compilation of Air Pollutant Emission Factors AP-42, Mobile Sources, Heavy-Duty Diesel Trucks," United States Environmental Protection Agency: Washington, D.C., June 1995. http://www.epa.gov/otaq/models/ap42/ap42-h7.pdf. (Accessed April 23, 2002.)

[EPA 1996]. *Gasoline and Diesel Industrial Engines- Emission Factor Documentation for AP-42: Compilation of Air Pollution Emission Factors, Vol. 1: Stationary Sources, Section 3.3: Gasoline and Diesel Industrial Engines, Supplement B*. Environmental Protection Agency: Washington, D.C., 1996.

[EPA 1997]. *1995 Toxics Release Inventory : Public Data Release*. Environmental Protection Agency Office of Pollution Prevention and Toxics: Washington, D.C., 1997.

[EPA 1998]. Beardsley, M. and C. Lindhjem. *Exhaust Emission Factors for Non-Road Emission Modeling- Compression Ignition*. Environmental Protection Agency: Washington, D.C., 1998.

[Friedrich 2002]. Friedrich, E. "Life-cycle Assessment as an Environmental Management Tool in the Production of Potable Water." *Water Science and Technology*, 46(Part 9), 29-36, 2002.

[IPCC 1999]. *Aviation and the Global Environment: Aviation Fuels*. Intergovernmental Panel on Climate Change. http://www.grida.no/climate/ipcc/aviation/109.htm (Accessed April 27, 2004.)

[John Deere 2004]. "Construction Equipment" home page. John Deere Corporation. http://www.deere.com/en_US/cfd/construction/deere_const/crawlers/deere_dozer_selection.html (Accessed January 15, 2004.)

[Matthews 2000]. Matthews, H. S. and L. B. Lave. "Applications of Environmental Valuation for Determining Externality Costs." *Environmental Science & Technology* 34(8): 1390-1395, 2000.

[Means 1997]. Page, J., ed. *Heavy Construction Cost Data*, 12th ed. R.S. Means Corporation: Kingston, MA, 1997.

[OECD 1997]. *The Environmental Effects of Freight*. Organization for Economic Cooperation and Development: Paris, France, 1997.

[OMB 1992]. *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Circular Number A-94.Office of Management and Budget. Washington, D.C., October 29, 1992.

[Peters 2003]. Peters, M.S.; Timmerhaus, K.D.; West, R. *Plant Design and Economics for Chemical Engineers*. 5th ed. McGraw-Hill: New York, 2003.

[Romano 1999]. Romano, D., D. Gaudioso, and R. De Lauretis, “Aircraft Emissions: A Comparison of Methodologies Based on Different Data Availability.” *Environmental Monitoring and Assessment*, 56: 51-74, 1999.

[Sorenson 1995]. Sorenson, L. and N. Kilde, *Waste Treatment and Disposal: Air Traffic*. 1995, Risoe National Laboratory, Systems Analysis Department; European Environmental Agency. http://eionet.eea.eu.int/aegb/cap08/b851.htm (Accessed January 22, 2002).

[Stokes 2004]. Stokes, J. “Life-cycle Assessment of Alternative Water Supply Systems in California.” Ph.D. Dissertation. University of California, Berkeley, 2004.

Appendix C. Case Studies

List of Figures

List of Tables

NOTE: The text in this Appendix is quoted from Dr. Stokes's PhD dissertation [Stokes 2004].

C.1 Case Study Selection

Case studies were chosen to evaluate the life-cycle implications of water supply in urban water systems. The Marin Municipal Utility District (MMWD) in Northern California and the City of Oceanside Water Utilities Department (OWD) in Southern California were chosen as case studies on the basis of data availability and quality. Both water utilities are urban, import a significant portion of their water, have recycled water programs, and either desalinate water currently or are planning to in the future. OWD's water supply is fairly typical of a Southern California system, with the exception of desalination which is not yet common. Water systems in Northern California are more diverse because rainfall patterns vary more in the region. MMWD, though not necessarily typical, was chosen as one of few systems which have a design for a possible desalination system to supply potable water.

Case studies were evaluated to demonstrate the power and flexibility of the WEST tool. In many cases, detailed information on system design was unavailable. In some cases, the utilities did not have the data requested, in others it was withheld for security reasons. Appropriate assumptions were made in the case studies when better data were unavailable. However, due to incomplete data, the final results likely underestimate the overall effects of these systems.

C.2 General Assumptions

This section discusses the assumptions used in the analysis of the case studies which follow. The conditions described are assumed to be true unless more specific information is available for a particular system.

C.2.1 Pipelines

A limited number of pipe sizes were included in the tool for simplicity. The following pipe diameters (in.) are included in the model: 1, 2, 4, 6, 8, 10, 12, 14, 18, 20, 24, 30, 36, 42, 48, 60, and 72. For pipe diameters smaller than 72 in. which are not listed, lengths were distributed proportionally to the diameters smaller and larger. For pipes with diameters larger than 72 in., data for 72 in. pipe were used.

In addition, pipes were consolidated into five common materials: asbestos cement (AC), concrete, DI, PVC, and steel. All plastic pipe was classified as PVC; metal pipe was allocated based on similar price. AC pipe, commonly used in water distribution systems, was banned in 1997 but still comprises a significant component of water distribution systems. As a result, no prices are available for this commodity. AC pipe was assumed to be equivalent to non-reinforced concrete pipe in both cost and size.

Cement-mortar lined pipe is assumed to include the mortar thicknesses listed in Table C.1 [Mays 2000]. These thicknesses are provided for concrete, DI and steel pipe.

Diameter (in.)	Mortar Thickness (in.)		
	Concrete	Ductile Iron	Steel
1-2	0.5	0.0625	0.32
4-10	0.5	0.0625	0.25
12	0.5	0.09375	0.25
14-16	0.5	0.09375	0.32
18-20	0.75	0.09375	0.32
24	0.75	0.09375	0.375
30-36	0.75	0.125	0.375
42-75	0.75	0.125	0.5

Table C.1 Mortar Lining Thickness [Mays 2000; Nayyar 2002]

Fittings (e.g., bends, wyes, tees, reducers) were assumed to be located on average every 0.25 miles for large-diameter pipe (14-in. or larger) and every 0.1 miles of smaller diameter pipe. For estimating purposes, all fittings were assumed to be ductile iron 90° bends.

Isolation valves are assumed to be placed every 0.75 miles of pipe if no other valve information is available. Butterfly valves are used for this purpose in large-diameter pipe; gate valves are used in pipe with diameters less than 14 inches. Pressure-regulating valves are located at every pumping facility. Every storage tank assumed to have one check valve and two altitude valves.

Cost information was available for butterfly, gate, check, and globe valves [Means 1997, Peters 2003]. Globe valves were used to estimate cost for all valves other than those listed. Most other valves are based on a globe or similar valve body type [Mays 2000].

Isolation and other pipeline valves are assumed to be housed in underground concrete valve boxes. Each box is assumed to house two valves on average. For pipe with diameters larger than 30 in., the valve boxes are assumed to be 100 ft^2 with a depth of 8 ft. or one ft. below the pipe bottom, whichever is deeper. If more than one valve is housed in the box, the area is assumed to increase by 25 ft^2 for each additional valve. The boxes are constructed of cast-in-place reinforced concrete. For pipes between 14 in. and 30 in. diameter, the boxes are assumed to be 50 ft^2 with an additional 10 ft^2 for each additional valve and a depth of one ft. below the bottom of the pipe. Small diameter pipes are assumed to be housed in boxes which are 10 ft^2 and 6 in. deeper than the bottom of the pipe. For pipe with diameters of 30 in. and smaller, pre-cast concrete boxes are installed.

C.2.2 Electricity Use

When specific data were not available, electricity use was based on the total estimated motor capacity in horsepower (hp) of pumps in the system plus an additional 15% for non-pumping electricity use (e.g., lighting, controls) for phases except potable distribution. Equation C.1 shows how electricity use was estimated:

Equation C.1 $$ElectricityUse = 0.36 * hp * 7.46 * 10^{-4} * Hrs * 1.15$$

Where Electricity Use is in MWh;

0.36 accounts for 60% pump and motor efficiency and pump operation at 60% of maximum capacity;

hp = maximum capacity of the pump motor;

$7.46*10^{-4}$ converts hp to MWh;

Hrs = the annual hours the pump operates; and

1.15 = an estimate of non-pumping electricity use.

If information on water pressures coming in and out of the pumps are known, a more accurate assessment could be made; however, this was not available.

C.2.3 Chemicals

Chemicals used in the treatment processes are assumed to have the following properties unless otherwise noted [ASCE 1998]. Chemicals are listed in alphabetical order.

Alum, or aluminum sulfate ($Al_2(SO_4)_3 * 12\ H_2O$), is commonly used as a coagulant in water treatment. It is available in liquid or powder form. The specific weight of liquid alum is 11.2 lb/gal.

Aqueous ammonia, or ammonium hydroxide (NH_4OH), is used along with a chlorine compound for disinfection. The process is known as chloramination. It has a density of 7.9 lb/gal and is typically sold in liquid form.

Calcium carbonate ($CaCO_3$) or limestone is used to raise pH for corrosion control. Calcium carbonate is sold in solid form.

Caustic soda, also known as sodium hydroxide (NaOH), is used to raise the pH of water. For example, effluent from treatment plants may be treated with caustic soda to prevent corrosion in distribution piping. Caustic soda is commonly sold as a liquid of 50% concentration. It has a density of 12.7 lb/gal.

Chlorine gas (Cl_2) is commonly used as a disinfectant in water treatment. It was used as the default disinfectant in this study if other information was not available. Chlorine can be purchased in various forms but for this study was assumed to be delivered as a pressurized gas. Chlorine gas is highly reactive and denser than air. As a result, chlorine requires special handling and storage. Other chlorine-based compounds such as sodium hypochlorite (a liquid) may be used for disinfection to avoid these issues.

Ferric chloride ($FeCl_3$) is used as a coagulant in water treatment processes. It is typically sold as a liquid with a concentration of approximately 40%.

Fluorosilicic acid (H_2SiF_6) is used to fluorinate water. Because fluoride is toxic, it is only added at very low doses. It is commonly sold as a 25% concentration liquid.

Hydrochloric acid (HCl) is used to control the pH during water treatment. It is sold in liquid form and typically used in a 20% concentration.

Polymers are high molecular weight, synthetic, organic compounds added to water to aid coagulation. They may be charged or neutral. Many are proprietary compounds and are commonly available in liquid form.

Sodium hypochlorite, or household bleach (NaOCl), is used as a disinfectant. It is usually a liquid of approximately 15% concentration. It is more commonly used in smaller treatment plants to avoid the safety issues associate with chlorine gas.

Sulfuric acid (H_2SO_4) is used for pH control during the treatment process. It is available in liquid form of various concentrations.

Zinc orthophosphate ($ZnPO_4$) is one of several phosphate-based chemicals used for corrosion control. It is available in liquid or solid form.

C.3 Marin Municipal Water District

The Marin Municipal Water District (MMWD) is the primary water supplier for southern Marin County, California, just north of San Francisco. A map of the service area is provided in Figure C.1. The service area receives 30 in. of rainfall a year and 50 in. of water in the neighboring Mount Tamalpais and West Marin watersheds.

Figure C.1 MMWD Service Area Map [MMWD 2004]

C.3.1 System Overview

The MMWD system information has been compiled from a variety of sources [MMWD 2003; MUWMP 2003; MMWD 2004; Theisen 2004]. Additional references for specific components of the water system are referenced in the appropriate sections.

In 2000, the MMWD served a population of 185,000 over a service area of 147 square miles. That same year the MMWD provided just over 31,000 AF of water through 59,000 service connections. Residential customers comprise 92% of the connections. Average annual use is 29,000 AF per year, or 26 million gal. per day (MGD).

The MMWD obtains water from a combination of local sources, importation, and reclamation and is considering augmenting or replacing the imported water supply with desalinated water. Precipitation collected in seven MMWD reservoirs located in its service area and in the neighboring West Marin and Mount Tamalpais Watersheds provides an average of 72% of its supplies. Rainfall varies significantly; as a result, water collected in reservoirs can fluctuate between 68% and 88% of annual water supply. Imported, recycled, and proposed desalinated water sources are described in detail below.

C.3.2 Imported Water

The MMWD imports raw water from the Russian River through contracts with the Sonoma County Water Agency (SCWA). This water accounts for 10% to 30% of the supply, with an annual average of 22%. In the 36 months between July 2001 and December 2003, the MMWD's supply of Russian River water averaged 8,100 AF per year (7.2 MGD) [Kauwe 2004]. When including the effects of necessary infrastructure improvements, the MMWD's Russian River water will cost $1,000 to $1,500 per AF.

Future supplies of imported water are threatened by competition with other agencies, particularly Sonoma County utilities and the North Marin Water District (NMWD). As demand in these agencies increases, supplies to the MMWD may be limited, particularly under drought conditions. Reliability concerns are described specifically in section C.2.3.7.

C.3.2.1 Supply

The MMWD's imported water is pumped through infrastructure owned and operated by three different agencies: the SCWA, the NMWD, and the MMWD. The supply infrastructure is described in the following sections.

C.3.2.1.1 Sonoma County Water Agency

The SCWA contract provides 9,300 AF each year (8.3 MGD) with an option for an additional 5,000 AF each year (4.5 MGD) which the MMWD must exercise in 2005 [MUWMP 2003; Jeane 2004]; on average, the MMWD uses 87% of its allotment [Kauwe 2004]. The following data on the SCWA's infrastructure were obtained primarily from SCWA officials [Jeane 2004].

SCWA extracts water from 60 to 80 ft. below the Russian River at two locations, Mirabel and Wohler [SCWA 2004]. Water sold to the MMWD is extracted from the Mirabel diversion site. It is assumed that there are six 16-in. diameter wells at Mirabel, each cased in stainless steel with a gravel pack.

At Mirabel, there are six 1,250-hp pumps in the system that supplies water to the MMWD and other SCWA customers; the output from 1.5 Mirabel pumps is typically pumping water sold to the NMWD and the MMWD. Approximately 60,000 AF per year (54 MGD), of water is extracted at Mirabel and Wohler on average. The Mirabel intake piping and controls are housed in ground-level pumphouses constructed from reinforced concrete. A portion of the water extracted at Mirabel is then transported through NMWD's aqueduct and sold to the MMWD.

Table C.2 summarizes piping, fittings, and valves for the connection between the Mirabel intake and the NMWD connection, a distance of over 20 miles. All pipe is cement mortar-lined and coated welded steel pipe (CMLS) and is assumed to be buried 5 ft. below ground surface (bgs). About five mainline isolation valves are located along the pipe alignment as shown in Table C.2. Each is housed in an underground vault.

Diameter (in.)	Length (ft.)	Fittings	Isolation Valves
48	18,100	14	1
36	12,400	11	1
30	87,000	66	3

Table C.2 SCWA Supply Infrastructure Summary [Jeane 2004]

Four storage tanks are located along the SCWA aqueduct in Cotati and Kastania. Table C.3 summarizes the dimensions of these tanks. Each tank is assumed have one check valve and two altitude valves. Three tanks are piped with 36-in. pipe; one with 30-in. pipe. The tanks are constructed of reinforced concrete.

Material	Number of Tanks	Average Tank Characteristics		
		Capacity (MG)	Depth (ft.)	Diameter (ft.)
Concrete	1	18	60	226
Concrete	2	12	50	202
Concrete	1	6	30	185

Table C.3 SCWA Water Tank Summary [Jeane 2004]

Two pump stations are located between the Russian River intake and the NMWD connection, Ely and Kastania. These are located at the north and south ends of Petaluma, respectively. The Ely Pump Station has a capacity of 1,000 hp using two 500-hp pumps and can pump approximately 30 MGD. The Ely Pump Station is not housed in a facility.

The Kastania Pumps Station has a capacity of 650 hp and is composed of one 400-hp and one 250-hp pump. This pump station can pump approximately 21 MGD. Each pump station includes a pressure regulating valve, one with a 36-in. diameter and the other with a 30-in. diameter.

Each year, approximately 6,000 MWh of electricity consumption is attributable to the MMWD's imported water supply from Mirabel. In addition, pumping the MMWD's water at Ely and Kastania Pump Stations consumes approximately 3,750 MWh each year. Electricity uses averages 1.2 MWh/AF.

C.3.2.1.2 North Marin Water District

The SCWA supply infrastructure connects with the NMWD in south Petaluma. The NMWD's aqueduct transports the imported water 9.5 miles to northern Novato before connecting with the MMWD's pipeline [NMWD 2004; Kauwe 2004]. The pipeline is composed of 50,000 ft. of 30-in. diameter welded steel pipe. The flow capacity is 21 MGD. The pipe is generally buried 3 to 4 ft. bgs but in certain places it is as deep at 12 ft. For the analysis, the pipe was assumed to be placed at 4 ft. bgs for the entire pipe length.

It is assumed that there are ten butterfly isolation valves and 38 fittings located along this pipeline. One flowmeter is assumed to be placed at the connection to the MMWD pipeline. Each valve is housed in an underground concrete vault. No pump stations or storage facilities are located along this aqueduct, therefore, electricity consumed by this system is minimal. A value of 15 MWh per year is assumed.

C.3.2.1.3 Marin Municipal Water District

The MMWD connects with the NMWD pipeline in northern Novato. The MMWD owns and operates 28,500 ft. of 36-in. diameter CMLS which transports water from the connection to the treatment facility.

The pipe is buried 2.5 to 3 ft. bgs and includes 22 fittings. The pipeline is assumed to have a capacity of 11 MGD, similar to the treatment facility [MBK 2002].

There are four butterfly isolation valves along the pipe alignment. These are housed in underground concrete valve boxes. No pump stations or storage facilities are located along the pipeline. As a result, electricity use is minimal and assumed to be 7 MWh.

C.3.2.1.4 Supply Infrastructure Summary

Table C.4 summarizes the infrastructure used to provide imported water to the MMWD.

System	Distance (miles)	Production (AF per year)	% of Water to the MMWD
SCWA	20	34,700	23%
NMWD	9.5	16,700	49%
MMWD	3	8,100	100%

Table C.4 MMWD Supply Infrastructure Summary

C.3.2.2 Treatment

Water supplied by the SCWA is from a fairly pristine source, therefore little treatment is needed to meet regulatory requirements. All Russian River water is processed through the Ignacio Treatment Plant (ITP). ITP facilities also include a small office and lab facility, approximately 100 ft^2 in area.

The ITP is less of a treatment plant than a pumping station. At the ITP, three pumps with a total of 16 MGD capacity operate as part of the distribution system. A corrosion control chemical (zinc orthophosphate), a fluoridation chemical (fluorosilicic acid), and disinfectant (chlorine and aqueous ammonia) are added to influent water at ITP. It is assumed that disinfectant contact time is achieved in the distribution system so no separate contact basin is present. These chemicals are added so the imported water matches effluent from the MMWD's traditional surface water treatment plants. No other treatment is needed.

Table C.5 summarizes chemicals added to the system at the ITP. Dosages for zinc orthophosphate, chlorine, and ammonia are based on requirements at other surface water treatment plants [OWD 2003; Cape Canaveral 2004]. Fluoridation information was obtained from the American Dental Association [ADA 2004]. Three 5,000 steel tanks are located on-site for chemical storage. Four 0.5-hp pumps, 200 ft. of 4-in. PVC pipe, and 300 ft. of DI pipe comprise the chemical delivery system.

Chemical	**Use**	**Annual Volume Consumed (lb)**
Zinc orthophosphate	Corrosion control	2,400
Fluorosilicic acid	Fluoridation	2,500
Chlorine	Disinfectant	178,000
Aqueous ammonia	Disinfectant	119,000

Table C.5 ITP Chemical Use [OWD 2003; Cape Canaveral 2004; ADA 2004]

Pumping at this location is classified into the distribution phase rather than the treatment phase because the pumping is not essential to the treatment process. A small amount of electricity, estimated at 25 MWh per year, is used to operate the chemical feed system, the office and lab facilities, and treatment system controls.

C.3.2.3 Distribution

The MMWD's potable water distribution system is extensive with 4.5 million ft. of potable water pipe. The system is used to distribute all potable water, including existing imported and local water sources and proposed desalinated water.

Distribution piping was estimated using data from the MMWD for 4.3 million ft. of pipe [Theisen 2004]. The data were analyzed by distributing unknown pipe types and diameters proportionally among known types, consolidating pipes which were similar in type, diameter, and price (e.g., some categories of steel pipe), and increasing final totals for each pipeline category by approximately 5% to reach a final total of 4.5 million ft. of potable water pipe. For simplicity, large diameter pipe (14 in. and larger) was assumed to be buried 3 ft. below the surface; smaller diameter pipe, 2.5 ft. Table C.6 provides estimated lengths, diameters, and material of distribution piping.

Diameter (in.)	Asbestos Cement (ft.)	Concrete (ft.)	Ductile Iron (ft.)	Polyvinyl Chloride (ft.)	Steel (ft.)	Fittings (Number)
1				1,358	12,680	27
2	283		10,154	19,529	154,134	349
4	20,662		543,574	17,284	146,481	1,379
6	145,889		1,052,364	126,584	341,086	3,156
8	85,424		474,476	93,484	349,356	1,900
10	10,205		75,348	776	14,292	191
12	320		111,072	555	254,654	695
14	821	819	36,720	29	55,615	179
18		20,636	1,719		92,030	217
20		2,180			35,030	71
24		6,011			101,364	204
30		8,297			38,153	88
36		5,578			16,191	42
48		29			763	2
60					17,081	33
72					167	1

Table C.6 MMWD Potable Distribution Pipe Summary (adapted from [Theisen 2004])

There are more than 60,000 valves of nine different types in the distribution system. The MMWD provided data for about 20,000 valves [Theisen 2004]. It was assumed that each tank in the system has two altitude valves and one check valve. The other valve types were distributed proportionally by pipe size. The data for the 20,000 valves were proportionately increased to reflect the 60,000 valves known to be in the system. Table C.7 summarizes types and diameters of valves. These valves are housed in 30,000 underground concrete valve boxes, assuming each box houses an average of two valves.

Diameter (in.)	Air Relief	Butterfly	Gate	Pressure Regulating	Relief	Blow-Off	Drain	Tank Valves	
								Altitude	Check
2						411			
4	53		1,853	83		1,624	21		
6	122		4,241	190			49		
8	73		2,556	114			30		
10	7		256	11			3		
12	27		933	42			11		
14	7	16,248		11			3		
18	8	19,770		13	147		3	99	38
20	3	3,216		4	48		1	32	10
24	8	4,640		12	138		3	93	53
30	3	2,007		5	60		1	40	31
36	2	314		2			2		
48		11							
60		246		2					
72		2							
Total	313	46,454	9,839	489	393	2,035	127	264	132

Table C.7 MMWD Potable Distribution Valve Summary (adapted from [Theisen 2004])

The system includes 98 pumps stations with 195 pumps used for potable and raw water. Eighteen stations are considered for transmission (large diameter) pipes. These stations include 49 pumps with a replacement value of $26 million (2003 dollars). Based on system model data, four of the transmission pumps' stations are used for raw water collected in reservoirs and are therefore outside the system boundary [MBK 2002]. Based on average data, potable water transmission is conducted using 14 pump stations with 38 pumps and a value of $1.4 million per pump station. Thirty percent of the costs are assumed to be due to pumps themselves. The remainder of cost is due to facilities, piping, and instrumentation and controls. These costs are assessed elsewhere in this analysis. A similar assumption as made for the distribution pump stations described in the following paragraph. No information is available on the motor capacity of the pumps.

Eighty smaller, distribution pump stations contain the remaining 146 pumps. These pump stations have a $46 million replacement value. The average motor capacity of the pumps is not known. The pump stations include a containment structure, piping, controls, and electrical equipment. Seventy-five percent of all pumps station structures are made of wood. Consequently, it is assumed that nine distribution pump stations are constructed with concrete and the remainder with wood.

The system includes 132 water tanks with a total capacity of 76.5 MG. Tanks are constructed of reinforced concrete, redwood, bolted steel, welded steel and riveted steel. Table C.8 summarizes estimated tank characteristics in the MMWD potable water distribution system. Estimates are made based on assessments of relative capacity of the materials to sustain the weight of water.

Material	Number of Tanks	Average Tank Characteristics		
		Capacity (MG)	Depth (ft.)	Diameter (ft.)
Concrete	2	5	30	168
Bolted steel	16	1	25	83
Other steel	64	0.75	25	71
Wood	50	0.05	15	24

Table C.8 MMWD Potable Water Tank Summary [Theisen 2004]

Electricity consumption in the distribution system is significant and is estimated to be 22,110 MWh annually. Due to the lack of information on distribution pump capacities, this estimate represents the remainder of electricity use after all other existing water supply phase components are removed.

C.3.2.4 Material Use Summary

Table C.9 provides information on all of the material inputs to the system which will be considered in the analysis. Costs are for the initial purchase of the component. All components are purchased once per service life except chemicals. Chemicals are purchased annually.

	SUPPLY						TREATMENT		DISTRIBUTION	
	SCWA		NMWD		MMWD					
	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)
Mortar	$ 3,600	1,407,700	$ 1,300	501,000	$ 900	342,700	$ -	-	$ -	-
Metal pipe and fittings	$ 6,306,000	10,307,000	$ 2,160,000	3,627,000	$ 1,391,000	3,103,000	$ 2,800	2,400	$ 47,892,000	59,622,000
Plastic Pipe	$ -	-	$ -	-	$ -	-	$ 2,500	900	$ 1,469,000	3,560,000
Concrete Pipe	$ -	-	$ -	-	$ -	-	$ -	-	$ 3,103,000	23,061,000
Metal valves	$ 367,000	61,500	$ 50,300	9,500	$ 22,400	6,000	$ 6,500	2,000	$ 129,909,000	16,940,000
Wood forms	$ 264,200	406,000	$ 7,700	11,800	$ 3,100	4,700	$ 13,100	20,100	$ 434,400	667,700
Wood tanks and pump stations	$ -	-	$ -	-	$ -	-	$ -	-	$ 1,426,000	3,110,000
Ready-mixed concrete	$ 1,500,000	40,472,000	$ 9,000	242,700	$ 3,600	97,100	$ 35,900	969,100	$ 2,763,000	74,522,000
Reinforcing steel	$ 1,517,000	3,074,000	$ 9,100	18,400	$ 3,600	7,400	$ 36,300	73,600	$ 2,793,000	5,660,000
Precast concrete	$ -	-	$ -	-	$ -	-	$ -	-	$ 50,160,000	234,862,000
Bolted steel tanks	$ -	-	$ -	-	$ -	-	$ -	-	$ 2,480,000	5,027,000
Other steel tanks	$ -	-	$ -	-	$ -	-	$ -	-	$ 7,360,000	14,918,000
Aggregate	$ 700	663,600	$ -	-	$ -	-	$ -	-	$ -	-
Pumps	$ 394,000	900	$ -	-	$ -	-	$ 3,500	100	$ 5,733,000	-
Measuring and metering devices	$ 1,100	1,000	$ 1,100	1,000	$ -	-	$ 1,200	1,500	$ -	-
Electrical	$ 21,000	-	$ 1,400	-	$ 600	-	$ 1,000	-	$ 3,573,000	-
Controls	$ 68,600	-	$ 4,600	-	$ 2,000	-	$ 3,300	-	$ 11,692,000	-
Landscape	$ -	-	$ -	-	$ -	-	$ 900	-	$ -	-
Tanks	$ -	-	$ -	-	$ -	-	$ 26,100	15,900	$ -	-
Industrial chemicals	$ -	-	$ -	-	$ -	-	$ 32,500	136,900	$ -	-

Table C.9 MMWD Imported Water Material Use Summary

C.3.2.5 Construction Equipment Use Summary

Table C.10 includes a summary of equipment use in the imported water system.

	Units	SUPPLY SCWA	NMWD	MMWD	TREATMENT	POTABLE DISTRIBUTION
Excavator						
JD200C	hrs	730	420	0	7	23,100
Cat 375	hrs	320	0	180	0	320
Crane	hrs	1,000	420	180	15	2,700
Loader	hrs	1,100	350	260	2	14,700
Plate Compactor	hrs	200	80	50	0.6	3,200
Concrete placement						
Pump	hrs	640	0	0	15	1,200
Vibrator	hrs	950	10	0	23	1,800
Truck	mi	2,400	410	160	1600	17,000
Soil Off-haul						
Dump Truck	mi	153,400	36,430	29,520	1300	1,550,200

Table C.10 MMWD Imported Water Construction Equipment Use Summary

C.3.2.6 Water Supply Reliability Concerns

Water purchased from the SCWA is delivered on an "as available" basis and is subject to restrictions when Russian River water levels are low. The water may be in short supply during drought periods.

Furthermore, future MMWD supply is limited by the capacity of the NMWD pipeline. As demand in the NMWD service area increases, less capacity is available for the MMWD. The MMWD is considering two plans to make future supply more reliable: incorporating local, desalinated supply (see Section C.3.3) and constructing a new pipeline to connect to the SCWA supplies. The new intertie would cost approximately $33 million and involve construction of eleven miles of pipeline, three pump stations, and 6 MG of storage [MMWD 2003]. The impact of the intertie construction was not assessed as a part of this research.

C.3.3 Desalinated Water

Currently, the MMWD is considering using a desalination plant to supply 5,000 to 15,000 AF of water annually (4.5 – 13 MGD) in place of imported water [Huffman 2001; URS 2003]. The following description assumes the 10,000 AF plant will be constructed, but major components are sized so the plant can be expanded to 15,000 AF. Several reports describe the proposed system [MMWD 1990; Sheikh 2001; URS 2003]. These documents are used to obtain information necessary for the current analysis. The proposed desalination system will provide water at a cost of $1,200 – $1,800 per AF.

C.3.3.1 Supply

The seawater intake is located at the end of a 2,034-ft. reinforced concrete pier. At the end of the pier, a platform of 24 ft. by 120 ft. supports the pumphouse. The pumphouse is assumed to be a 1,500 ft^2 concrete structure. The pier is supported by 9-ft^2 reinforced concrete piles which are driven into rock, an average 75 ft. below the pier deck. The piles are placed approximately every 40 ft. along the pier for a total of 120 piles. Pumps are extended and screened 18 ft. below the deck. Four 250-hp, 3-MGD pumps and two 500-hp, 6-MGD pumps with adjustable frequency drives and necessary electrical and control equipment are installed to obtain the seawater. Two 30-in. raw water PE pipelines are attached to the pier to transport water to the plant site. Onshore, the pipes converge into a 36-in. raw water pipeline which carries water 1.2 miles to the plant site. The pipeline contains four 30-in. fittings and five 36-in. fittings.

The system contains two 30-in. butterfly isolation valves, one 36-in. butterfly isolation valve, and two 30-in. pressure regulating valves. The 36-in. valve is housed in an underground vault.

Electricity necessary to operate the intake pumps and control equipment is included in the operation phase. It is estimated to be 3,795 MWh per year. The maintenance phase includes chemicals used for monthly intake and pipeline cleaning as well as replacement parts.

C.3.3.2 Treatment

Water is desalinated through an RO process. Facilities at the desalination plant include a 2,000-ft^2 RO equipment building and a 3,000-ft^2 auxiliary building containing an office, laboratory, warehouse, and chemical storage. The proposed treatment processes and equipment are illustrated in Figure C.2.

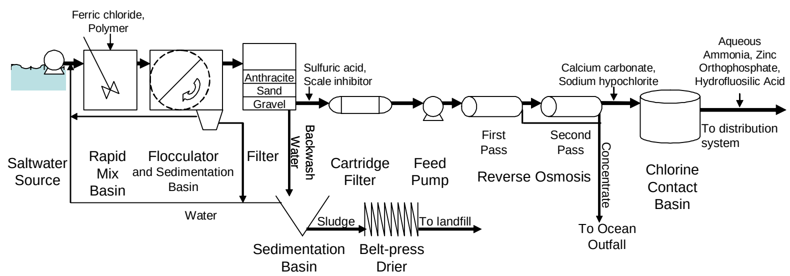


Figure C.2 MMWD Desalination Process

Influent water is “pre-treated” prior to undergoing the RO process. Ferric chloride and polymer are added to the raw water in the rapid mix basin to aid coagulation. The water is then processed through a propeller flocculator and sedimentation basin. Flocculated water is passed through two stages of multimedia filtration (12 in. of sand, 24 in. anthracite coal, and 18 in. of support gravel). Sulfuric acid is added to the filtered water to lower the pH. A scale inhibitor is added to complete the pre-treatment process.

Pre-treated water goes through cartridge filters. Filters must be changed often; about 3,000 cartridge filters are used annually. Six 1,000-hp, high-pressure feed pumps increase the pressure to the required 700 to 1,000 pounds per square inch (psi). The water under pressure enters the two-pass RO system. This system is composed of 5 treatment trains. Annual RO membrane costs are $702,400 (2001 dollars). All water is treated in the first pass of the RO process. Approximately half the water is treated further by the second pass. This design provides an overall product recovery of 50%; as a result, approximately 10 MGD of concentrated brine must be disposed.

Product water from the RO process is post-treated with calcium carbonate to improve taste, control pH, and prevent corrosion. Sodium hypochlorite is added and water is stored in a chlorine contact basin to achieve the required disinfection. Aqueous ammonia is added to further disinfect the water before it enters the distribution system.

Brine is disposed through an ocean outfall. A 30-in. PE pipeline carries water 0.6 miles to an outfall where it is diluted with treated wastewater from the Central Marin Sanitation Agency before being discharged to the bay. One butterfly isolation valve is located in the plant on the outfall piping. The pipeline has 10 fittings and is buried 3 ft. bgs. A pump station containing two 150-hp pumps is also constructed. A 0.3-mile outfall of 84-in. diameter reinforced concrete pipe has also been constructed and will continue to be used for wastewater discharge. As a result, construction and operation of the outfall itself are excluded.

Table C.11 summarizes the assumed sizes of various treatment facilities in the system. All basins are assumed to be constructed of concrete. Components are sized based on industry standards [ASCE 1998].

Component	Number	Surface Area (ft^2)	Depth (ft.)
Mix basin	1	144	14
Flocculator	7	400	14
Sedimentation basin	3	2,800	2
Filter	8	520	14
Chlorine contact basin	1	6,000	14

Table C.11 MMWD Desalination Component Sizes (based on [ASCE 1998])

Energy use, chemical production, and sludge and filter disposal needed to operate the system are included in the operation phase. Table C.12 summarizes assumed chemical use quantities [URS 2003; ADA 2004; Cape Canaveral 2004; OWD 2003]. The chemical delivery system at the plant is assumed to consist of eight 0.5-hp pumps. Chemicals in liquid form are stored in eight 2,000-gal. steel tanks; powdered chemicals are stored in the delivery container.

Chemical	Use	Annual Volume Consumed (lb)
Ferric chloride	Coagulant	610,000
Polymer	Coagulant	6,100
Sulfuric acid	pH control	1,220,000
Polyelectrolyte	Filtration aid	15,000
Proprietary	Scale inhibitor	244,000
Zinc orthophosphate	Corrosion control	36,600
Fluorosilicic acid	Fluoridation	2,500
Sodium hypochlorite	Disinfectant	30,000
Aqueous ammonia	Disinfectant	126,000
Sodium Hypochlorite	Cleaning	2,000
Calcium Carbonate	pH control	365,000

Table C.12 MMWD Desalination Chemical Use (adapted primarily from [URS 2003])

Backwashing filters produces waste water (1.5 to 2.5 MGD) which is processed through a gravity settling and thickening process. Sludge from the process is combined with sludge from the sedimentation basin and dewatered in a belt-press drier. Recovered water is processed through the plant again. Dried sludge is then transported in dump trucks to a landfill assumed to be located 20 miles away. About 17 tons of dewatered sludge will be produced daily.

According to one report, the desalination supply and treatment system would use 43,825 MWh annually [Sheikh 2001]. Based on this value and the estimate of supply system electricity consumption, the desalination treatment process is expected to use 38,460 MWh each year.

C.3.3.3 Distribution

Potable water from the desalination plant is assumed to be distributed to customers through the same distribution system used for imported water. Therefore, the distribution system is analyzed as if the entire existing distribution system is included in the analysis as if the entire system were used to transport desalinated water, as this source will likely replace most or all imported water. In addition, infrastructure to connect the desalination plant to the distribution system is considered. The current potable distribution system is designed to transport water from west to east. As the desalination plant would be located on the east side of the service area, additional piping, storage, and pumps stations would have to be constructed [MMWD 1990].

To connect to the existing distribution system, 3,500 ft. of 18-in. pipe, 16,000 ft. of 24-in. pipe, and 49,000 ft. of 30-in. pipe will be installed. These pipelines would connect to the San Rafael and Ross Valley demand centers. These pipes are assumed to be steel and buried 4 ft. bgs. Table C.13 summarizes pipe lengths and assumed fitting and valve requirements.

Diameter (in.)	Length (ft.)	Fittings (number)	Isolation Valves (number)
18	3,500	3	1
24	16,000	12	4
30	49,000	37	12

Table C.13 MMWD Desalinated Water Distribution Piping [MMWD 1990]

Eleven underground concrete vaults will be constructed to house the valves.

In addition, three pump stations would be installed. One pumps station containing four 150-hp pumps would connect the plant to the first tank. A second 125-hp pump station would connect the two tanks. A third pump station containing two 150-hp pumps would carry water from the tanks to Ross. The pump stations would be housed in above-ground concrete structures. Each pump station is assumed to contain one pressure regulating valve, requiring a total of two 30-in. valves and one 24-in. valve.

Four 2-MG storage tanks would be constructed; each is assumed to be constructed of reinforced-concrete and 25 ft. deep with an 82 ft. diameter. Each tank requires one check valve and two altitude valves. All are assumed to be 30-in diameter.

In the distribution phase, 22,110 MWh are used to operate the existing distribution system and 2,220 MWh are needed for the additions.

C.3.3.4 Material Use Summary

Table C.14 provides information on all of the material inputs to the recycled water system which will be considered in the analysis. Default service lives, listed in Table B.1, were used for the analysis except that RO membranes were assumed to have a service life of 5 years [URS 2003]. Costs presented are for initial purchase only. Additional purchases for all components are made at the end of the service life with the exception of chemicals which are purchased annually.

	SUPPLY		TREATMENT		DISTRIBUTION	
	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)
Metal pipe and fittings	$ 25,700	11,300	$ 100,600	80,100	$ 2,734,000	4,632,000
Plastic pipe	$ 695,100	489,900	$ 260,200	144,100	$ -	-
Metal valves	$ 50,300	6,600	$ 32,500	14,600	$ 219,400	26,000
Wood forms	$ 132,400	203,500	$ 126,200	194,000	$ 98,700	151,800
Ready-mixed concrete	$ 666,200	17,971,400	$ 222,200	5,993,000	$ 556,900	15,023,000
Steel	$ 673,400	1,365,000	$ 224,600	455,200	$ 563,000	1,141,100
Precast concrete	$ -	-	$ -	-	$ 11,400	54,000
Pumps	$ 440,000	700	$ 26,300	2,400	$ 102,000	1,100
Metering Pumps	$ -	-	$ 6,900	100	$ -	-
Measuring and metering devices	$ 1,200	3,300	$ 3,300	100	$ -	-
Electrical	$ 167,600	-	$ 29,600	-	$ 6,000	-
Controls	$ 57,700	-	$ 96,900	-	$ 19,700	-
Landscape	$ -	-	$ 26,900	-	$ -	-
Tanks	$ -	-	$ 27,800	26,800	$ -	-
Industrial Chemicals	$ -	-	$ 165,300	919,500	$ -	-
Polymers	$ -	-	$ 2,700	2,800	$ -	-
Chems and preps	$ -	-	$ 230,000	117,500	$ -	-
Lime	$ -	-	$ 22,200	165,600	$ -	-
Sand and gravel filter media	$ -	-	$ 117,400	68,400	$ -	-
Anthracite filter media	$ -	-	$ 208,000	33,000	$ -	-
RO membranes	$ -	-	$ 644,200	-	$ -	-
Filter membranes	$ -	-	$ 20,200	-	$ -	-
Steel filter casing	$ -	-	$ 6,700	-	$ -	-
Industrial equipment	$ -	-	$ 10,500	-	$ -	-

Table C.14 MMWD Desalination Material Use Summary

For material delivery, default values, also in Table B.1, were used and the methodology described in C.2.6 was followed.

C.3.3.5 Construction Equipment Use Summary

Construction equipment use was evaluated as described in Section C.2.5. All construction equipment use occurs only at the beginning of the project with the exception of sludge disposal, which occurs annually. Table C.15 provides a summary of construction equipment use.

	Units	SUPPLY	TREATMENT	DISTRIBUTION
Excavator				
JD200C	hrs	0	60	560
Cat 375	hrs	40	0	30
Crane	hrs	40	90	560
Loader	hrs	60	80	520
Plate compactor	hrs	10	10	110
Concrete placement				
Pump	hrs	0	90	240
Vibrator	hrs	280	140	350
Truck	mi	420	10,000	2,100
Off-haul dump truck	mi	30,100	10,100	64,000
Sludge disposal				
Loader	hrs		30	
Dump truck	mi		30,100	

Table C.15 MMWD Desalination Construction Equipment Use Summary

C.3.4 Recycled Water

In conjunction with the Las Gallinas Valley Sanitation District (LGVSD), the MMWD provides 240 customers with 700 AF per year (0.62 MGD), or about 2% of its annual supply, of recycled water. The facility is located in the northern portion of the MMWD's service area and serves San Rafael's downtown area. The water is primarily used for landscape irrigation but some is also used for toilet-flushing and a commercial car wash. Based on a projected budget for 1995–2003, the operational costs of producing the MMWD's recycled water are approximately $450 per AF [MMWD 1995]. However, when capital expenditures are included, the cost is between $1,800 and $2,000 per AF.

C.3.4.1 Supply

Water is supplied from the LGVSD's WWTP. In 2003, effluent from the WWTP had an average pH of 7.13 and turbidity of 7.8 nephelometric turbidity units (NTU) [Joe 2004]. Figure C.3 shows the treatment process the water undergoes prior to recycling at the WWTP. The influent is treated through a grit chamber and a series of clarifiers, biofilters, reactors and filters. Water is disinfected prior to discharge. Sludge from the clarifiers is treated in digesters and then stored in sludge storage ponds. However, treatment at the WWTP is not included in the system boundary.

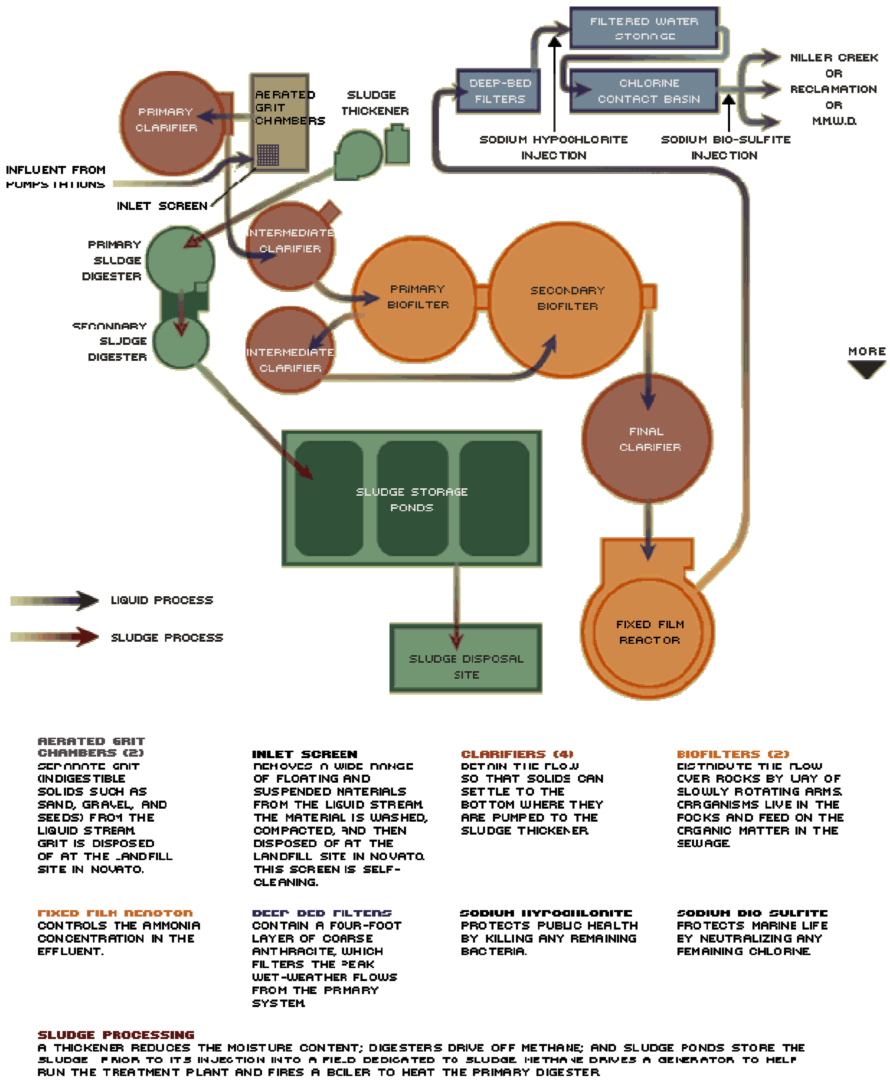


Figure C.3 LGVSD Wastewater Treatment Schematic [LGVSD 2004]

Water is recycled at an adjacent 2-MGD facility. Water is assumed to be transported between the WWTP and recycling plant with 2,500 ft. of 12-in diameter welded steel pipe buried 3 ft. bgs. The pipeline also includes four fittings, one isolation valve, and one pressure regulating valve. One 150-hp pump is assumed to be used to transport the water between facilities. Electricity consumed based on this assumption is approximately 390 MWh annually.

C.3.4.2 Treatment

The direct-filtration Las Gallinas Recycling Plant (LGRP) has a capacity of 2 MGD but is currently operating at approximately half of its capacity. A 500-ft^2 office and laboratory facility is located at the treatment plant site.

At LGRP, alum and polymers are mixed into the influent water as coagulants. Filtration is assumed to occur in seven dual-media filters composed of 12 in. of sand, 24 in. of anthracite coal, and 18 in. of support gravel. The filters operate in parallel. Each filter has a surface area of 100 ft^2. At full capacity, one filter is always out of service for backwashing. At current utilization, four filters are typically used each day. Filter size is based on a typical design flowrate of 2 gal/min-ft^2 [ASCE 1998]. In practice, the design flowrate may exceed 2 gal/min-ft^2 but only if the higher rate is approved by regulators. Filter basins are constructed of reinforced concrete.

Filters are backwashed using an upflow system with surface wash [ASCE 1998]. Each filter is assumed to be backwashed daily, producing almost 50,000 gal. of backwash water each day; at full capacity, twice as much would be produced. Backwash water is assumed to be discharged to two 1,800 ft^2 concrete settling basins where it is stored for at least 24 hours. Sludge is then processed through a belt-press drier and disposed in a landfill assumed to be located 30 miles away. LGRP is assumed to dispose of 20 tons of sludge annually.

Following filtration, zinc orthophosphate is added for corrosion control, caustic soda for pH control, and chlorine for disinfection. Table C.16 estimates annual chemical use at this facility as it was estimated for the ITP except for caustic soda use. Caustic soda use was estimated based on use at a Southern California treatment plant [MWD 2004]. The optimal range for the effluent pH is 6.5 to 7.5 [ASCE 1998]. Four 1,000 gallon steel tanks are on-site for chemical storage.

Chemical	Use	Annual Amount Consumed (lb)
Alum	Coagulant	35,000
Polymer	Coagulant	4
Zinc orthophosphate	Corrosion control	26,400
Caustic Soda	pH control	3,900
Chlorine	Disinfectant	16,000

Table C.16 LGRP Chemical Use [OWD 2003; Cape Canaveral 2004; ASCE 1998; MWD 2004]

The LGRP includes two 25-hp pumps and one 10-hp pump for water transport. Six 0.25-hp pumps are included as part of the chemical feed system. Electricity is consumed at the LGRP for pumping, chemical addition, office and laboratory use, and to operate system controls. Approximately 165 MWh of electricity are used in plant operations each year.

C.3.4.3 Distribution

The non-potable distribution system consists of 25 miles of pipeline connecting the recycled water plant with central San Rafael. A list of pipe segments sorted by diameter and material was provided by the MMWD. The length of each segment was not provided. However, the general manager of the MMWD stated that the distribution system is composed primarily of a combination of 6-in and 8-in pipe of CMLS and PVC. To estimate the length of pipe of each diameter and material, 6-in. and 8-in. CMLS and PVC pipe are assumed to comprise 85% of the non-potable distribution system and each segment of these pipe categories was estimated to be 235 ft. long. Pipes of other sizes and materials were assumed to be 55 ft. long. All pipes whose size and material comprised less than 0.5% of the overall system were combined into a similar category for simplicity.

Table C.17 summarizes the composition of the non-potable distribution system based on these assumptions. Distribution pipe is assumed to be buried an average of 3 ft. bgs.

Diameter (in.)	Material (ft.) PVC	CMLS	Fittings (number)	Gate Valves (number)
1		13,001	2	
2		1,900	4	
4		2,400	5	
6	42,000	28,000	133	18
8	24,000	20,000	84	11
10		1,300	2	
12	4,200	6,700	21	3

[1] Numbers may not sum due to rounding.

Table C.17 MMWD Non-potable Distribution System Summary [Theisen 2004]

Sixteen underground concrete vaults are constructed to house an average of two valves per box.

The distribution system also contains 1.7 MG of storage. Two steel tanks hold a total of 1 MG and three concrete vaults store another 0.7 MG. Each tank has one check valve and two altitude valves. All valves are assumed to have 8-in. diameters. Tank details are summarized in Table C.18.

Material	Number of Tanks	Average Tank Characteristics Capacity (MG)	Depth (ft.)	Diameter (ft.)
Concrete	3	0.23	25	40
Steel	2	0.5	25	58

Table C.18 MMWD Recycled Water System Tank Summary (based on [Theisen 2004])

Four pump stations contain ten pumps used in the recycled water distribution system. The pump stations include one 50-hp pump, three 100-hp pumps, two 25-hp pumps, two 15-hp pumps, and two 40-hp pumps. Each pump station is assumed to contain an 18-in. pressure regulating valve. Pump station facilities are assumed to be constructed of concrete. The recycled distribution system consumes an estimated 1,325 MWh each year.

C.3.4.4 Material Use Summary

Table C.19 provides information on all of the material inputs to the recycled water system which will be considered in the analysis. All costs represent initial costs only. All materials are replaced at the end of their service life with the exception of chemicals which are purchased annually.

	SUPPLY		TREATMENT		DISTRIBUTION	
	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)
Mortar	$ -	-	$ -	-	$ 250	97,400
Metal pipe and fittings	$ 27,700	72,400	$ 5,590	4,790	$ 768,200	988,300
Plastic pipe	$ -	-	$ 4,970	1,780	$ 449,600	1,146,700
Metal valves	$ 3,620	290	$ 2,440	1,000	$ 15,600	1,990
Wood forms	$ -	-	$ 25,200	38,700	$ 24,100	37,000
Ready-mixed concrete	$ -	-	$ 42,800	1,155,100	$ 95,500	2,576,200
Reinforcing steel	$ -	-	$ 43,300	87,700	$ 96,500	195,700
Precast concrete	$ -	-	$ -	-	$ 12,600	38,300
Pumps	$ 15,000	160	$ 12,300	280	$ 60,900	1,130
Metering Pumps	$ -	-	$ 3,120	190	$ -	-
Measuring and metering devices	$ 530	-	$ 690	70	$ -	-
Electrical	$ 530	-	$ 2,010	-	$ 2,100	-
Controls	$ 1,720	-	$ 6,570	-	$ 6,880	-
Landscape	$ -	-	$ 1,830	-	$ -	-
Tanks	$ -	-	$ 13,900	9,480	$ 195,000	395,300
Industrial Chemicals	$ -	-	$ 13,600	36,900	$ -	-
Sand and gravel filter media	$ -	-	$ 19,800	13,200	$ -	-
Anthracite filter media	$ -	-	$ 35,000	6,350	$ -	-
Industrial equipment	$ -	-	$ 3,000	6,000	$ -	-

Table C.19 MMWD Recycled Water Material Use Summary

C.3.4.5 Construction Equipment Use Summary

Table C.20 summarizes construction equipment use for the recycled water system. All equipment use occurs at the initial construction except sludge disposal which occurs annually.

	Units	SUPPLY	TREATMENT	DISTRIBUTION
Excavator				
JD200C	hrs	15	13	683
Crane	hrs	-	20	-
Loader	hrs	7	12	312
Plate Compactor	hrs	2	1	86
Concrete placement				
Pump	hrs	-	18	40
Vibrator	hrs	-	27	61
Truck	mi	-	1,935	262
Off-haul dump truck	mi	284	1,649	9,805
Sludge disposal dump truck	mi	-	120	-

Table C.20 MMWD Recycled Water Construction Equipment Use Summary

C.3.5 Electricity Use Summary

In 2003, the MMWD water supply system used 26,000 MWh, costing $3.6 million, including the supply, treatment, and distribution phases. Almost 4,000 MWh of additional electricity was consumed by the SCWA to supply water to the MMWD system. The proposed desalination system is excluded from this value.

Table C.21 provides an estimate of the electricity used in each phase of the water supply system. For the imported supply values, the numbers represent the MMWD's share of the electricity used in the supply system. When a specific value was unavailable, the electricity use was estimated based on hours of use and rated capacity in hp (see Section C.2.3). The motor rating and pump use assumed for the calculation is listed in the table when appropriate. Local supply and treatment includes pumping between reservoirs and operation of the San Geronimo and the Bon Tempe Treatment Plants; these are outside the system boundary. After electricity use estimates were made for the imported supply and treatment systems and the recycled water systems, unallocated electricity was assigned to the potable distribution system. Desalination energy use is estimated based on current RO technology.

Water Supply Phase	Pump Motor Rating (hp)	Pump Use (hrs)	Electricity Consumption (MWh)
Imported Supply			9,770
Current MMWD System			
Local Supply	2,250	1,344	935
Local Treatment	400	8,423	1,040
Imported Treatment	10	8,423	25
Potable Distribution	---	---	22,110
Recycled Supply	150	8,423	390
Recycled Treatment	63	8,423	165
Recycled Distribution	510	8,423	1,325
Proposed Desalination System			
Supply	1,750	8,423	3,795
Treatment	---	---	38,460
Distribution[1]	1,025	8,423	24,330

[1] Includes energy necessary to operate the existing potable distribution system and 2,220 MWh necessary to operate additional infrastructure.

Table C.21 MMWD System Electricity Use Summary (estimated from [Theisen 2004; Jeane 2004; URS 2003]

C.4 City of Oceanside Water Utilities Department

Oceanside is a coastal community located in northern San Diego County, 35 miles north of the city of San Diego. A map of the area is provided below in Figure C.4 [OWD 2001]. The area receives an average of 10.3 in. of rainfall annually [World Climate 2004].

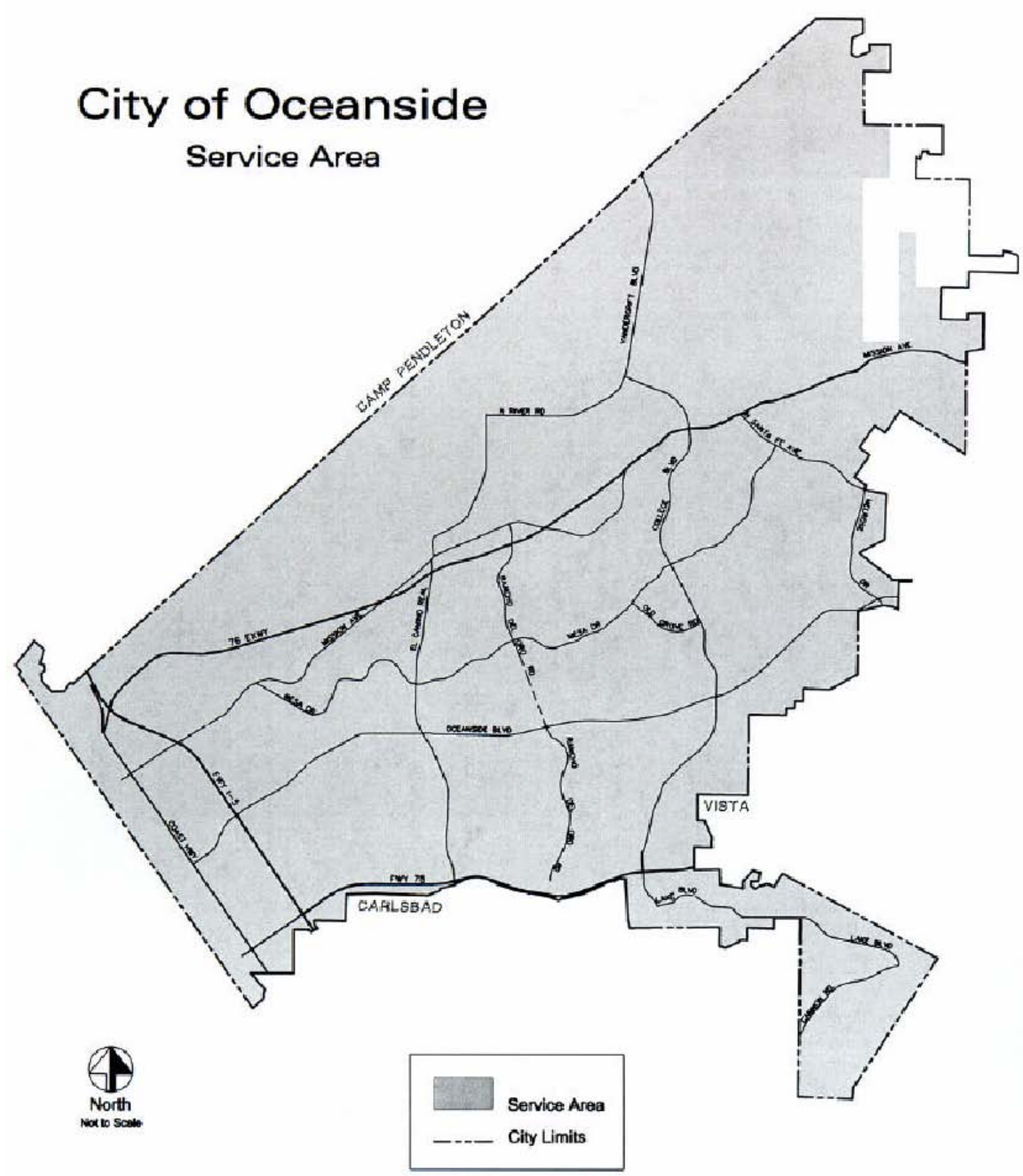


Figure C.4 OWD Service Area Map [OWD 1999]

C.4.1 System Overview

The City of Oceanside Water Utilities Department (OWD) is a member of the San Diego County Water Authority (SDCWA). The OWD serves a population of approximately 160,000 people and a service area of about 44 square miles [OWD 2001]. In fiscal year 2002 – 2003 the OWD provided 32,900 AF of water (29 MGD) [OWD 2003]. Data on the OWD system were collected from a variety of sources [OWD 1999; OWD 2001; OWD 2003]. Other sources are cited specifically below. Figure C.5 provides water consumption classified by end-use category.

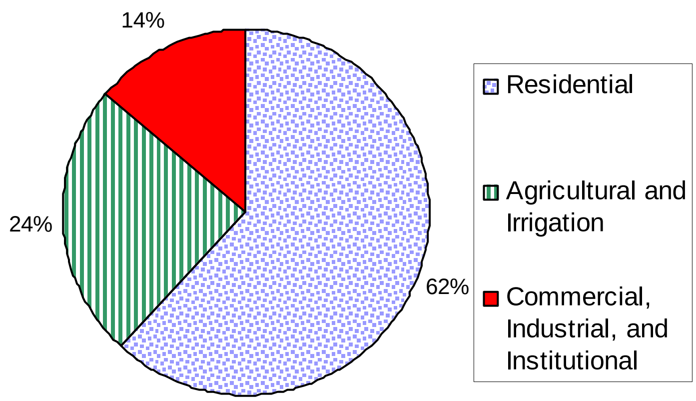


Figure C.5 OWD Water Consumption by Customer Category [OWD 2001]

The OWD obtains 92% of its water from imported sources, 8% from desalinating groundwater; and less than 1% from recycled water.

C.4.2 Imported Water

Because Oceanside is located in an arid environment, local supplies are not sufficient to meet its water demand. The majority of the OWD's water supply is transported hundreds of miles to its end-user.

The definitions of supply and distribution set forth in Section 3.1 have been altered for this analysis. For the OWD system, water is assumed to be transported by the supply system until the OWD extracts it as treated water from the water wholesaler's system (i.e., final ownership by the OWD, rather than treatment, divides the supply and distribution systems).

In addition, valves and fittings for the supply infrastructure are excluded from the analysis. These components are negligible compared to the overall system, especially considering the small proportion of processed water supplied to the OWD.

C.4.2.1 Supply

Ninety-two percent or approximately 30,200 AF (27 MGD) of the OWD's 2002 – 2003 supply of drinking water is imported through the SDCWA. The year 2002 numbers are expected to be typical of future imported water demand because they reflect increased production of desalinated water. The SDCWA provides the OWD with 35% treated and 65% raw water. The raw water is treated at a plant owned and operated by the OWD. This plant typically experiences 15% water loss. Therefore, the OWD purchases a total of 32,240 AF (29 MGD) of water from the SDCWA in a typical year. The SDCWA contracts with MWD to supply water from the CRA and the SWP. Figure C.6 is a schematic of the sources of the OWD's imported water.

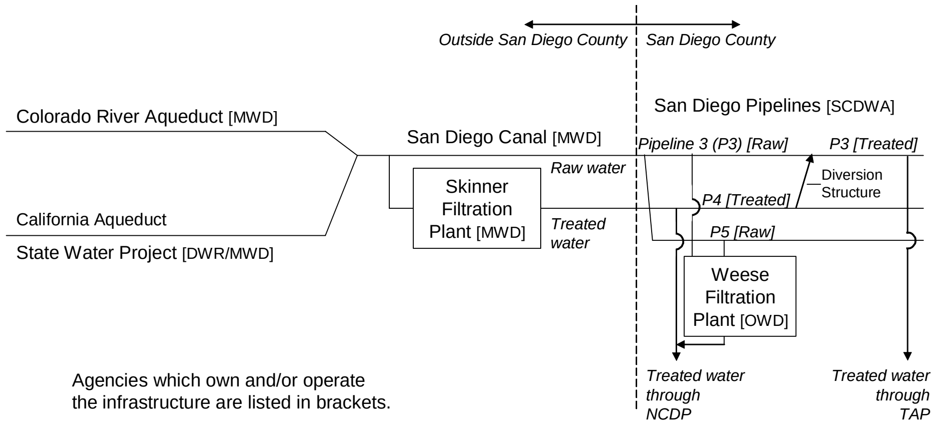


Figure C.6 OWD's Imported Water Supply

Finding new water supplies is very important to Southern California water utilities that rely on imported water. Without new supplies, MWD expects that water shortages will occur every other year [MWD 1996].

C.4.2.1.1 Colorado River Aqueduct

The OWD receives at least 75% of their imported water supply (22,650 AF per year or 20 MGD) from the CRA. The water costs $220 per AF on average for raw, or untreated, water. MWD owns and operates the 242-mile aqueduct (capacity: 1,800 cfs) which originates at Lake Havasu at the Nevada and California border. Water enters the San Diego Canal approximately 20 miles before the CRA terminates at Lake Mathews in Riverside County [MWD 2000]. In a typical year, the CRA provides 1.2 MAF (1100 MGD) of water to Southern California. Information about the CRA was compiled from a variety of sources [MWD 1996; MWD 2000; MWD 2004]. Other sources are cited specifically in the text. Figure C.7 shows the infrastructure associated with the CRA.

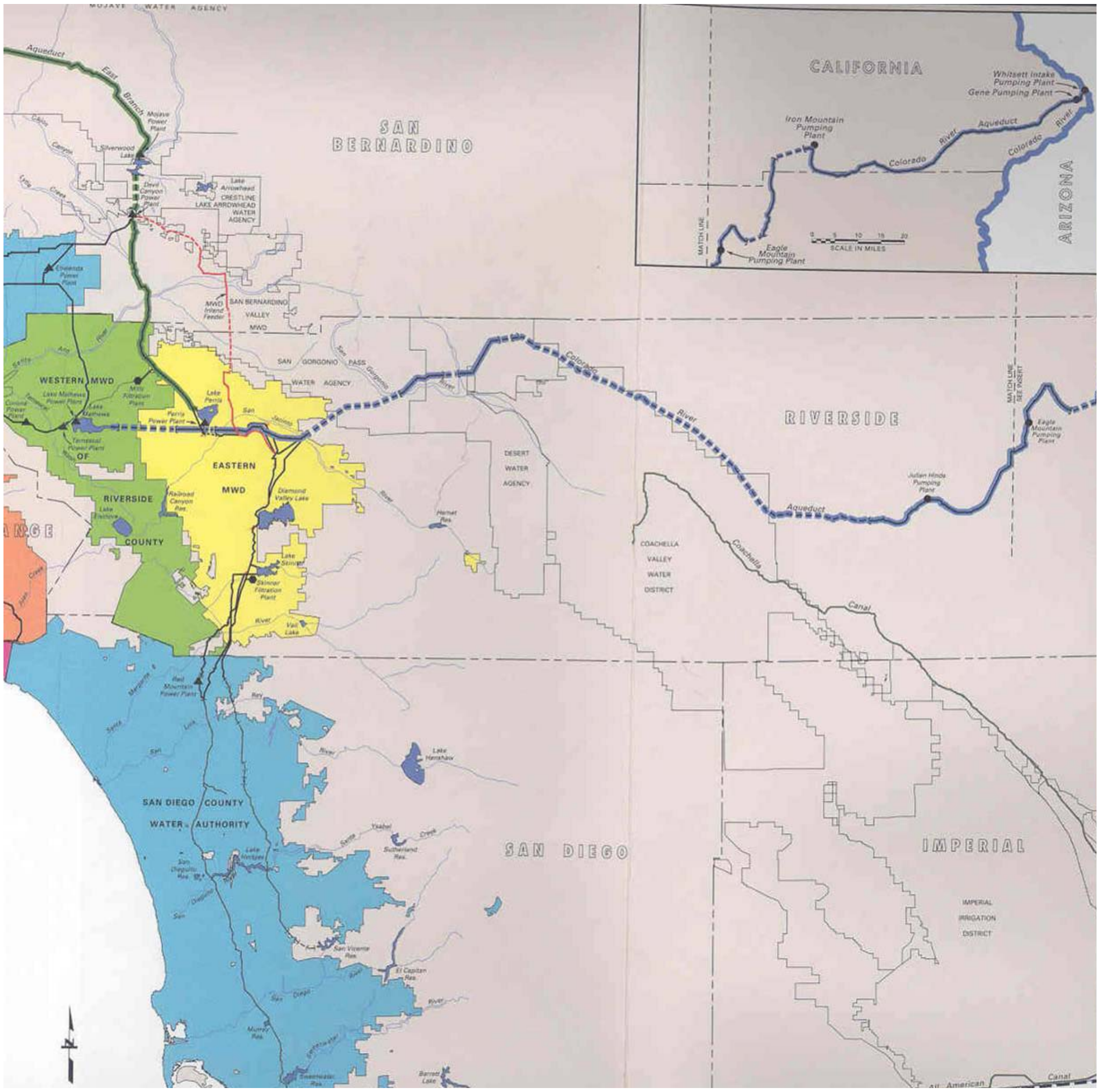


Figure C.7 Colorado River Aqueduct System Map [MWD 2000]

Parker Dam, which created Lake Havasu, was constructed primarily to provide water to the CRA and the Central Arizona Project. About half of the water extracted from the reservoir is used by MWD. Parker Dam is a 320-ft high concrete arch dam with 73% of its height underground. The crest of the dam is 856 ft. long. The dam is 39 ft. thick at its crest and 100 ft. thick at its base [Parker Dam 2004].

The CRA is a mix of canals, tunnels, conduits, and siphons. Between Lake Havasu and the diversion structure for the San Diego Canal, there are 63 miles of canals, 82 miles of tunnels, 55 miles of conduit, and 14 miles of pressurized pipe, or siphons. Figure C.8 describes the CRA aqueduct dimensions between Lake Havasu and the San Diego Canal.

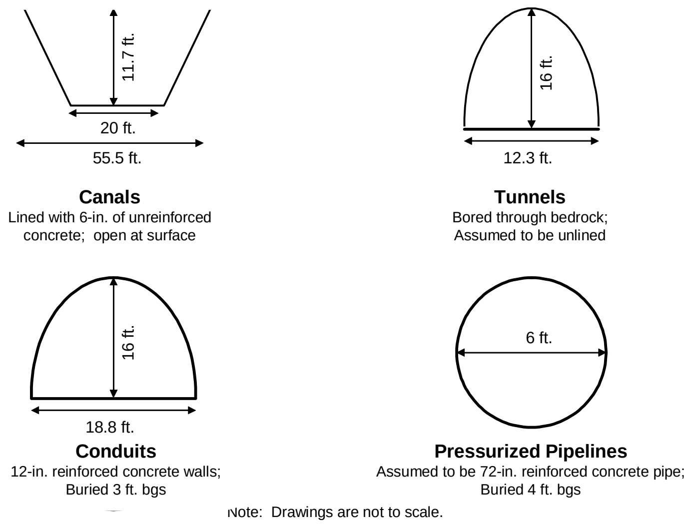


Figure C.8 CRA Aqueduct Materials [MWD 2004]

Average dimensions for canals, tunnels, and conduits, and assumed dimensions of pressurized pipe are shown in Figure C.8. Canal lining is assumed to be 6 in. thick. Some tunnels are lightly lined in concrete, however, the lining was excluded from the analysis due to insufficient data. Most pressurized pipelines are reinforced concrete pipe but some are steel. The pipe diameter varies. For simplicity, the pipe is assumed to be 72-in. diameter concrete pipe along the entire 14 miles.

A small reservoir is located adjacent to the Iron Mountain Reservoir. It stores 108 AF and is impounded by a 5-ft. high earth-fill berm. The construction of this facility was not included in the analysis because due to its size. The reservoir has an insignificant effect on the results estimated for OWD.

Five pumping plants are located along the aqueduct. Each pumping plant has a capacity of 1.2 MAF per year (1100 MGD). All pumping plants have nine pumps – eight operating and one on stand-by for maintenance. All pumps have a nominal capacity of 225 cubic feet per second (cfs) or approximately 145 MGD. Details about each of the five pump stations are provided in Table C.22.

Pump Station	Elevation change (ft.)	Total Motor Rating (hp)
Whitsett	291	81,000
Gene	303	81,000
Iron Mountain	144	38,700
Eagle Mountain	438	112,500
Julian Hinds	441	112,500

Table C.22 CRA Pumping Plant Summary [MWD 2004]

At the Hinds Pumping Plant, water reaches it ultimate elevation of 1,807 ft. above sea level. Water then flows 116 miles to its terminal reservoir by gravity.

Pumping CRA water to the San Diego Canal requires 2 MWh/AF of electricity [MWD 2000; Wilkinson 2004]. In a typical year, the CRA's operation uses 2,400,000 MWh.

C.4.2.1.2 State Water Project

The remainder of Oceanside's imported water (7,550 AF per year or 6.7 MGD) is obtained from the Feather River through the SWP at a cost of $300 per AF of raw water. The following information about the SWP was compiled from a variety of sources [Wilkinson 2004; SWP 2002; MWD 2000; MWD 1996]. Other sources are cited specifically as needed.

The SWP consists of infrastructure owned and operated by the California Department of Water Resources (DWR) in conjunction with local utilities, including MWD. These agencies are contractually obligated to repay all capital and operating costs associated with providing their water. Typically, the SWP provides 4.93 MAF of water (4400 MGD) to 23 million people throughout the state and its water is used to irrigate 600,000 acres of farmland [SWP 2002]. The SWP facilities are extensive and include 28 dams and reservoirs, 662 miles of aqueduct, and 17 pumping plants [SWP 2002]. Figure C.9 shows the major facilities in the SWP.

Figure C.9 SWP System Map [SWP 2002]

Figure C.10 summarizes Year 2000 water deliveries from the SWP contracts.

Figure C.10 SWP Water Deliveries [SWP 2002]

For the purposes of this analysis, only infrastructure south of the Banks Pumping Plant is considered. The northern SWP facilities, while necessary for Southern California water supply, would have been constructed for hydropower purposes and to supply water to the local population and therefore are excluded [Wilkinson 2004]. In 2000, 1.28 MAF of water (1150 MGD) was delivered to contractors located north of the Banks Pumping Plant.

The OWD's water is extracted from the San Joaquin Delta at the Banks Pumping Plant. It flows through the 444-mile long main-line California Aqueduct to its terminal reservoir at Lake Perris. The California Aqueduct delivers 2.95 MAF of water (2600 MGD) to Central and Southern California if water for the

Coastal and West Branches is excluded. There are 7 storage facilities and 8 reservoirs on the path between the Northern California delta and the connection to MWD's San Diego Canal.

The OWD water is transported the full length of the California Aqueduct. This aqueduct consists of 391 miles of canals, channels, and reservoirs, 41 miles of pipelines, and 12 miles of tunnels. For simplicity, canals, pipelines, and tunnels are assumed to be constructed as described for the CRA (see Section C.4.2.1.1 and Figure C.8).

Storage facilities which are included in the SWP and process water used by the OWD are summarized in Table C.23. Three of these dams (San Luis, O'Neill, and Los Banos) are jointly owned with the U.S. Bureau of Reclamation (USBR). USBR uses the reservoirs to store water for the Central Valley Project (CVP). Half of San Luis Reservoir storage is for the CVP water; it is assumed that half the storage available in O'Neill Forebay and Los Banos Reservoir is also used by USBR. The dams at San Luis, O'Neill, Los Banos, Silverwood, and Perris are earth-fill construction [Dams 2004; USBR 2004]. It is assumed that the others are as well.

	Capacity (AF)	Surface Area (Acres)	Structural Height (ft.)	Crest Length (ft.)	Structural Volume (cy)
Clifton Court Forebay	31,000	2,100	30	36,500	2,400,000
Bethany Reservoir	5,100	180	120	3,900	1,400,000
San Luis Reservoir[1]	20,000,000	12,520	385	18,700	77,645,000
O'Neill Forebay[1]	56,000	2,300	88	14,000	3,000,000
Los Banos Reservoir[1]	35,000	2,300	167	1,370	2,100,000
Silverwood Lake	75,000	980	249	2,230	7,600,000
Lake Perris	130,000	2,300	128	11,500	28,000,000

1 Co-owned with USBR.

Table C.23 SWP Reservoir and Dam Summary [SWP 2002]

Pumping plants which provide water to the OWD are described in Table C.24. The number of pumps required for each plant is estimated assuming all have a motor capacity of 12,500 hp.

Pumping Plant	Head (ft.)	Flow (cfs)	Total Motor Rating (hp)
Banks	244	10,670	333,000
Gianelli	213	11,000	504,000
Dos Amigos	116	15,450	240,000
Buena Vista	205	5,405	144,500
Teerink Wheeler Ridge	233	5,445	150,000
Chrisman Wind Gap	518	4,995	330,000
Edmonston	1,926	4,480	1,120,000
Pearblossom	543	2,575	203,200

Table C.24 SWP Pumping Plant Summary [SWP 2002]

The SWP is the single largest user of power in the state. Figure C.11 summarizes the electricity use at pumping plants along the California Aqueduct. The branch terminating at Devil Canyon is relevant for the OWD water supply.

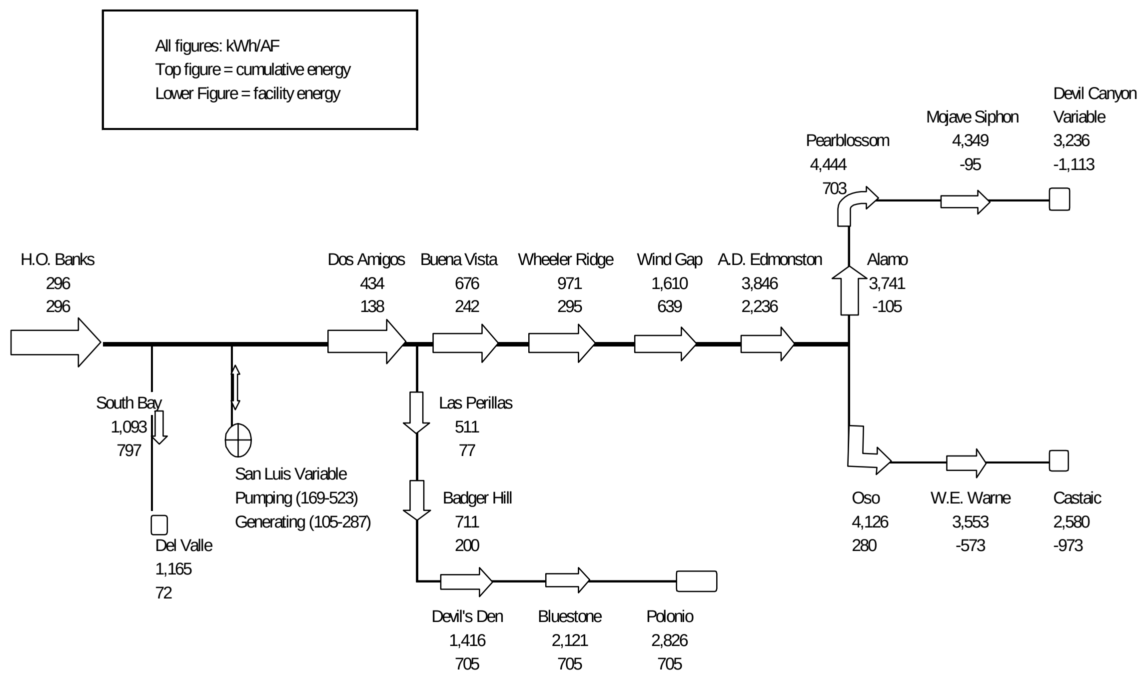


Figure C.11 SWP Energy Used for Pumping [Wilkinson 2004]

The final energy consumption values account for energy recovered from the water at the Alamo, Mojave, and Devil Canyon Power Plants. Power plant construction, operation, and maintenance are not included in the system boundary.

The branch called "San Luis Variable" in Figure C.11 connects the SWP infrastructure to the O'Neill Forebay, San Luis Reservoir and Los Banos Reservoir. As a result, the branch is relevant for supplying water to Southern California. San Luis Reservoir pumping varies depending on storage requirements. Rather than exclude this electricity consumption from the assessment, values for both pumping and generating energy were chosen from the middle of the range shown in Figure C.11. Pumping and generating energy were estimated to be 326 kWh/AF and 196 kWh/AF, respectively. The net energy consumption was estimated at 130 kWh/AF. Half of the electricity use was assumed to be allocated to the USBR. Summing half of the net electricity consumption from the San Luis Branch and the total consumption from the Devil Canyon Branch, the SWP water consumes 3.3 MWh of electricity per AF. For deliveries occurring on the mainline California Aqueduct, the total electricity consumption is almost 10,000,000 MWh per year.

C.4.2.1.3 San Diego Canal

Water from the SWP and the CRA is transported to San Diego County through the San Diego Canal. For the SWP water, water from Lake Perris is transported via pipelines to the Casa Loma Canal and then to the San Diego Canal. A new connection between Lake Silverwood and the San Diego Canal, the Inland Feeder, is expected to be completed in 2007 but was not included in the analysis. A connection to the CRA occurs 20 miles east of Lake Mathews near the San Jacinto River. Figure C.7 shows the location of the San Diego Canal. In a typical year, the San Diego Canal is assumed to transport 700,000 AF (625 MGD).

The San Diego Canal terminates at Lake Skinner near Temecula, California. Fifty miles of canals comprise the San Diego Canal. The canals are assumed to be constructed as described in Section C.4.2.1.1 and illustrated in Figure C.8. At Lake Skinner, a portion of the water is treated at an MWD filtration plant. Raw water from Lake Skinner and the San Diego Canal and treated effluent from the treatment plant enter separate pipelines of the SDCWA Second Aqueduct (see Section C.4.2.1.4).

Water is stored in two locations along the San Diego Canal: Diamond Valley Lake and Lake Skinner. Diamond Valley Lake was constructed to improve supply reliability in the event of an earthquake by contributing significant storage west of the San Andreas Fault. The lake stores 800,000 AF. Diamond Valley Lake was constructed with three earth and rock fill dams: West, East, and Saddle Dams [DVL 2004].

In addition, 40,000 AF of storage is available at Lake Skinner. Skinner Dam, which creates Skinner Lake, is also an earth-fill dam [USBR 2004]. The dimensions of these dams are summarized in Table C.25. The structural volume for the dams is estimated based on the dimensions of dams in the SWP system that are similar in height.

Dam	Structural Height (ft.)	Crest Length (ft.)	Structural Volume (cy)
West[1]	285	8,300	25,547,400
East[2]	185	10,900	18,508,895
Saddle[3]	130	2,300	894,444
Skinner[3]	109	5150	1,679,252

[1] Based on dimensions of Sisk dam at the San Luis Reservoir.

[2] Based on the dimensions of Los Banos Dam.

[3] Based on the dimensions of Bethany Dam.

Table C.25 San Diego Canal Reservoir and Dam Summary [DVL 2004; USBR 2004]

In the winter, excess water from the San Diego Canal will be pumped to Diamond Valley Lake. The Diamond Valley Lake's Wadsworth Pumping Plant is composed of twelve 5,000-hp pumps capable of extracting 1,000 cfs from the CRA control structure [Temecula 2004]. These pumps do not operate continuously but are expected to operate approximately 25% of the year. Based on their operation schedule, the Wadsworth Pumping Plant will consume 8,100 MWh each year.

C.4.2.1.4 San Diego County Second Aqueduct

Once water reaches San Diego County, it is sold from MWD to the SDCWA. The SDCWA owns operates two aqueducts which supply water to San Diego County; these are known as the First and Second Aqueducts. The OWD is served off the Second Aqueduct which contains three pipelines (Pipelines 3, 4, and 5). In fiscal year 2001 –2002, the SDCWA purchased 585,600 AF (520 MGD) to be transported through the Second Aqueduct; this value is assumed to be typical. Figure C.12 shows the SDCWA infrastructure.

Figure C.12 SDCWA System Map for Northern San Diego County [SDCWA 2002]

Each of the three pipelines carries a portion of the water used by the OWD. Two (Pipelines 3 and 5) carry raw water while the remaining pipeline transports treated water from Skinner Filtration Plant. The North County Distribution Pipeline (NCDP) transports treated water from Pipeline 4 and effluent from the OWD's Weese Filtration Plant to four SDCWA agencies: the OWD, the Vista Irrigation district (VID), the Rainbow Municipal Water District, and the Vallecitos Water District.

A diversion structure located on the Second Aqueduct between the NCDP and the Tri-Agencies Pipeline (TAP) sends treated water from Pipeline 4 to Pipeline 3 such that south of the diversion structure, Pipeline 3 carries treated water. The TAP pulls treated water from Pipeline 3 and transports it to three agencies: the OWD, the VID, and the Carlsbad Municipal Water District.

Table C.26 summarizes pipe length and diameter for the portion of the Second Aqueduct relevant for the OWD water supply as well as the NCDP and the TAP.

Diameter (in.)	Steel (ft.)	PCCP (ft.)
20		10,665
30		12,250
36		9,900
48		106,000
54		82,758
60	10,630	41,380
72	82,835	75,210

Table C.26 SDCWA Pipe Summary [SDCWA 2003]

A 1-MG regulatory storage structure is located along the NCDP just outside of Weese. The facility is an above-ground concrete structure. It is assumed to be 15 ft. deep with a diameter of 108 ft. The tank is equipped with one check valve and two altitude valves, assumed to be 48 in. in diameter. These valves are included in the assessment because the OWD water represents a significant portion (77%) of water transported by the NCDP.

Water in the SDCWA system flows by gravity. As a result, electricity use was excluded, as the OWD's share of the consumption will be negligible.

C.4.2.1.5 Supply Infrastructure Summary

Table C.27 summarizes the capacity and use of the supply infrastructure serving the OWD.

Water Provider	OWD Water Provided (AF)	Total Water Provided (AF)	OWD Share (%)
Metropolitan Water District			
Colorado River Aqueduct	24,180	1,300,000	2%
SWP California Aqueduct	8,060	2,950,000	0.3%
San Diego Canals	32,240	700,000	5%
San Diego County Water Authority			
Second Aqueduct	32,240	585,640	6%
NCDP	20,500	26,650	77%
TAP	8,530	19,650	43%

Table C.27 OWD Supply Infrastructure Summary

C.4.2.2 Treatment

The SDCWA provides the OWD with 65% raw water and 35% treated water. The raw water is treated at the OWD's Weese Filtration Plant (Weese). Treated water is processed at MWD's Skinner Filtration Plant (Skinner). These are discussed in the following sections.

C.4.2.2.1 Weese Filtration Plant

The SDCWA untreated water is processed at the OWD's Weese Filtration Plant, located northeast of Oceanside, California. The following information on this facility is obtained from a variety of sources [MWD 1996; OWD 1999; OWD 2001; OWD 2003].

Weese is a direct filtration plant designed with a 16.5 MGD capacity but the plant can be successfully operated at 25 MGD. In the year 2000, Weese produced 18,020 AF (16 MGD); this is assumed to be typical. All treatment basins are constructed of reinforced concrete. Figure C.13 outlines the treatment process at Weese. In addition to process facilities, the plant also includes a 1,800-ft^2 chemical storage building, a 2,000-ft^2 office and laboratory building, and a 2,000-ft^2 chemical storage pad.

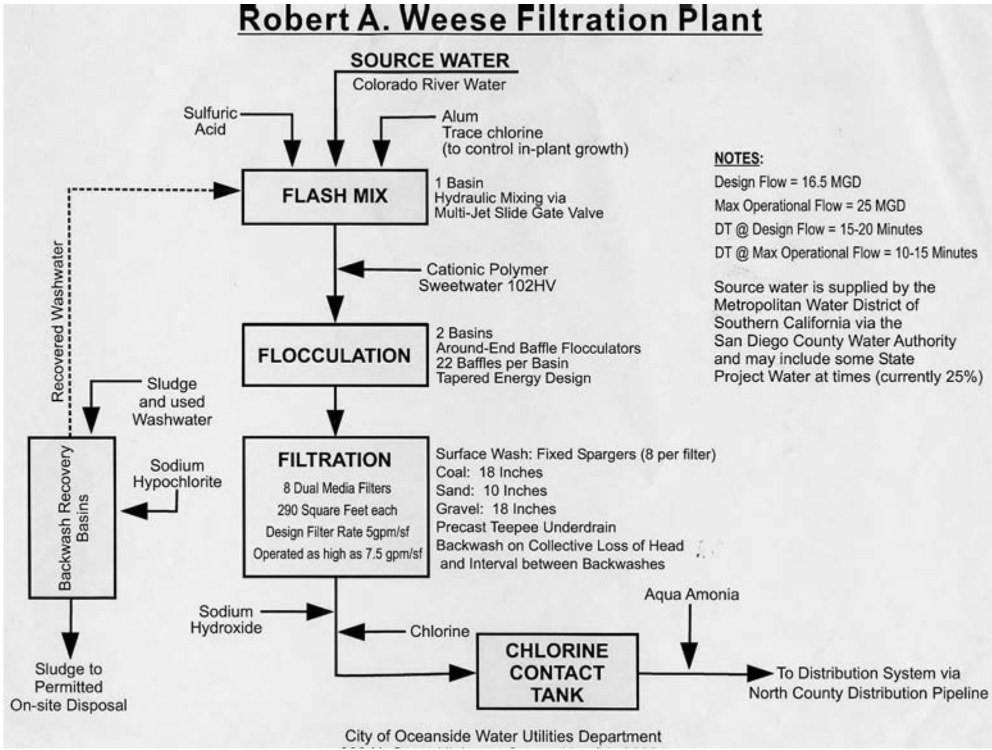


Figure C.13 Weese Treatment Schematic [OWD 2003]

A blend of the SWP and CRA water from the SDCWA's Second Aqueduct travels approximately 1,000 ft. through a 24-in. steel pipe to the treatment plant. The influent and effluent pipes are buried at 4 bgs. The water travels through the treatment process entirely by gravity. Alum, sulfuric acid, and trace amounts of chlorine are added in the rapid mix basin where water is mixed by its own velocity with a multi-jet slide gate. Water is split equally into two around-end baffle flocculators with 22 baffles per basin.

After flocculation, water flows equally into one of eight dual-media filters. The filters contain 18 in. of support gravel, 10 in. of sand, and 18 in. of anthracite coal. The design filter rate is 5 gal/min-ft^2. Caustic soda, or sodium hydroxide, is added to adjust the pH. Dosage varies based on influent quality.

Water is then disinfected with chlorine and sent to an underground contact chamber. The contact chamber contains three around-end baffles to increase residence time. Aqueous ammonia is added immediately prior to discharge to provide a chloraminated disinfection residual. Finally, the water travels 500 ft. through a 48-in. steel pipe to the SDCWA water storage tank where it is added to the NCDP.

Backwash water from the filters flows to a primary settling basin and then to two secondary settling basins. Each basin is approximately 300 ft2. The recovered backwash water is pumped back through the treatment plant after being disinfected by sodium hypochlorite. Sludge is collected from the settling basins about once a month and is stored in a permitted, on-site landfill. The sludge is not hazardous.

The majority of the effluent from Weese is sold back to MWD and enters the NCDP. The OWD buys back the treated water it needs from the NCDP at a later point on the pipeline. On a given day, if Weese produces more water than Oceanside needs, the water is sold to another utility served off the NCDP. However, on an annual basis, all water produced at Weese is used by the OWD.

Table C.28 summarizes the size of the treatment facilities at the Weese plant.

Component	Number	Surface Area (ft^2)	Depth (ft.)
Mix basin	1	9	12
Flocculation basin	2	1,000	12
Filters	8	290	12
Chlorine contact basin	1	9,000	15
Backwash settling basin	3	300	1.5

Table C.28 Weese Component Sizes [OWD 2003]

Annual chemical use is summarized in Table C.29. Caustic soda use is estimated based on consumption at Skinner. Both plants use the similar influent water, although the mix of CRA and SWP water may be different. The plant is assumed to contain six 0.5-hp chemical delivery pumps and seven chemical storage tanks of different sizes – two 1,000-gal., one 1,500-gal., one 2,000-gal., one 5,000-gal., and two 6,500-gal. tanks.

Chemical	Use	Annual Amount Consumed (lb)
Aluminum sulfate	Coagulant	850,000
Sulfuric Acid	pH control	306,000
Cationic polymer	Coagulant	98,175
Caustic soda	pH control	100,300
Chlorine	Disinfectant	40,000
Aqueous ammonia	Disinfectant	268,080
Sodium hypochlorite	Backwash disinfectant	104,100

Table C.29 Weese Chemical Use [OWD 2003; MWD 2004]

Weese used $62,300 in electricity in 2003. Assuming electricity costs of $0.1064 per kWh, the same as the MWD power, the Weese plant uses 586 MWh annually [MWD 2004].

C.4.2.2.2 Skinner Filtration Plant

Treated water purchased treated from the SDCWA is processed at MWD's Skinner Filtration Plant (Skinner) located in Riverside County [MWD 1996; MWD 2004]. Skinner processed a total of 315,000 AF (280 MGD) in 2000, the last year for which data is available. This value was assumed to be typical. Water sold to the OWD is 3.5% of the total water production at this plant.

In addition to treatment process structures, Skinner also includes an administrative building (15,000 ft^2) and three buildings that serve as warehouses and service buildings. (10,000 ft^2 each). The areas for these buildings are estimated.

Raw water treated at Skinner is pulled from the San Diego Canal and Lake Skinner. The plant consists of three conventional treatment modules in Plant 1 and three direct filtration modules in Plant 2. Six Venturi-style flowmeters measure flow through the system. Full conventional treatment includes rapid mix, flocculation, sedimentation, filtration, and disinfection. Figure C.14 illustrates the conventional treatment process. Direct filtration is essentially the same except it excludes the sedimentation process.

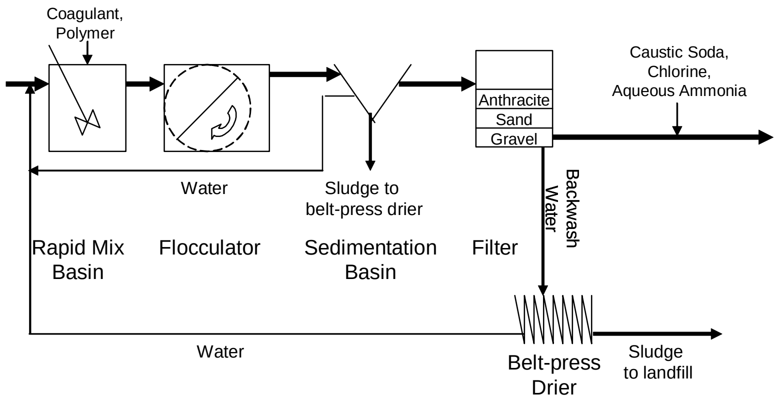


Figure C.14 Skinner Conventional Treatment Schematic

The conventional treatment plant, Plant 1, includes Modules 1, 2, and 3 and has a capacity of 240 MGD. In the year 2000, the last year for which complete data are available, Plant 1 processed 153,000 AF or an average of 136 MGD. Water entering the plant undergoes a rapid-mix process accomplished using multi-jet slide gates (two per module). Mechanical, impeller type mixers are also available but are seldom needed. During rapid mix, ferric chloride and three different polymers (cationic and non-ionic) are added to influent water to facilitate coagulation.

Each module in Plant 1 is then equipped with two parallel flocculation basins. Each basin includes six vertical-shaft, dual-speed mixers which operate continuously, for a total of 36 mixers in Plant 1. Twenty-four of the mixers are hydrofoil-type and twelve are impeller-type. After flocculation, the water then enters sedimentation basin.

Each module contains 18 self-backwashing filtration units – a total of 16 dual-media filters and 38 tri-media filters. The dual media filters contain 18 in. of support gravel, 8 in. of sand, and 20 in. of anthracite coal. The tri-media filters contain 18 in. of support sand, 3 in. of support gravel, 3 in. of garnet or ilmenite sand, 8 in. of silica sand, and 20 in. of anthracite coal.

Following filtration, water is disinfected with chlorine and caustic soda is added to adjust the pH. Ammonia is added to the plant effluent to provide a disinfectant residual in the distribution system. No chlorine contact basin is present.

Plant 2, the direct filtration plant, has a total capacity of 280 MGD and includes Modules 4, 5, and 6. The plant processed 162,000 AF (140 MGD) in 2000. Specifically, in Plant Two, rapid mixing is also accomplished using multi-jet slide gates. Modules 5 and 6 also have pumped diffusion mixers available. Module 4 has no mechanical mixer. Chemical addition is similar to Plant 1.

Plant 2 includes one flocculation basin per module. In Module 4, the basin includes 8 vertical impeller-type, dual-speed flocculators. Modules 5 and 6 have 12 vertical-plate, variable-speed flocculators. The flocculators are separated by over/under baffles. Following flocculation, the water passes directly to the filtration process without sedimentation. Plant 2 includes 18 dual-media and 36 tri-media filters. Filter design, disinfection and other post-treatment processes are similar to Plant 1.

In 2000, 65,221 backwashes occurred on the 108 filters. Backwash water is reclaimed in with a flocculation and settling process. Solids are then gravity-thickened and dewatered using two belt presses. In the year 2000, the belt presses operated 11,000 hours (hr) and produced 2,340 tons of sludge. Dewatering produced 5,900 MG of water which was returned to the treatment plant influent.

The plant produced a total of 10,000 tons of sludge to be hauled off-site in 2000. Sludge was assumed to have been hauled 20 miles to a non-hazardous landfill.

All treatment basins are constructed of reinforced concrete. The dimensions of the basins are summarized in Table C.30.

Component	Number	Surface Area (ft^2)	Depth (ft.)
Mix basins	12	100	12
Flocculation basins			
	6	4620	12
	1	6079	22.4
	2	11700	14.6
Sedimentation basins	6	17,682	12
Filters			
	36	350	12
	36	420	12
	36	553	12

Table C.30 Skinner Component Sizes [MWD 2004]

Chemical use and water production data for the period from January to June 2001 were used to establish the amount of each chemical used to produce each AF of water. The values were verified with chemical use data for the period July 2002 to June 2003. This chemical use factor was used to estimate chemical use for 2000. Total annual chemical use is provided in Table C.31. The system also includes six 5,000-gal. steel tanks and thirty-six 0.5-hp chemical feed pumps.

Chemical	Use	Annual Amount Consumed (lb)
Ferric chloride	Coagulant	3,478,980
Polymer	Coagulant	2,470,010
Caustic Soda	pH control	2,806,000
Chlorine	Disinfectant	4,543,939
Ammonia	Disinfectant	649,026
Sodium hypochlorite	Backwash disinfectant	818,766

Table C.31 Skinner Chemical Use (based on [MWD 2004])

Electricity use data were provided for 2003. Based on these data, it was determined that the plant uses 20 kWh/AF of water treated. For the year 2000, it was expected that the plant used 6,200 MWh.

C.4.2.3 Distribution

Pipe lengths were provided by the OWD in the form of the number of feet for each pipe diameter and for each material separately. Allocation of material types to pipe diameters was done manually by the author based on industry standards. Pipe information is summarized in Table C.32. All distribution pipe is assumed to be buried 3 ft. bgs.

Diameter (in)	Asbestos Cement (ft)	Concrete, mortar-lined (ft)	Concrete (ft)	Ductile Iron (ft)	Polyvinyl Chloride (ft)	Steel (ft)	Fittings (Number)
1					87		1
2				4,445	4,628		17
4	34,030			7,651	27,395		131
6	324,752			14,504	65,228		766
8	1,239,197			35,168	67,238		2,541
10	286,647			14,589	57,634		680
12	129,018			29,543	48,925		393
14	108,649			33,389	21,632		124
18				75,643	44,988		91
20			2,789	6,753	3,416	4,136	13
24			137,541	4,013		3,462	110
30		2,058	29,806			6,148	29
36		5,682				1,894	6
48		4,043					3

Table C.32 OWD Potable Distribution Pipe Summary (adapted from [OWD 2003]

System valve information was adapted from information provided by the OWD. The OWD provided the author with the number of each type of valve throughout the entire system. The valve totals were allocated according to proportion of pipe material and valve function. This is summarized below in Table C.33.

Diameter (in)	Air Relief	Butterfly	Gate	Pressure Regulating	Blow-Off	Check	Tank Valves	
							Altitude	Check
2			2		157			
4			104	1	512			
6	8		1,134	1		7		
8	28		3,794	13		22		
10	7		1,076	5		6		
12	4		597	4		3		
14	3	459		13		3		
18	3	338		7		2	8	4
20		48		7		1	8	4
24	3	407				2	8	4
30	2	107				1		
36	2	21						
48		6						
Total	60	1,386	6,707	38	669	47	24	12

Table C.33 OWD Potable Distribution Valve Summary (adapted from [OWD 2003]

Assuming pressure regulating valves are all housed at pump stations, tank valves at tanks, and the remaining valve boxes house an average of two valves, 4,400 underground valve boxes are needed.

Most water is distributed by gravity. However, four pump stations are used to provide water to the Morro Hills area routinely and certain other sectors during peak demand periods. In addition, five pump stations are maintained for use in emergencies. Each pump station houses an average of 2.5 pumps. Table C.34 summarizes the details on pumps housed in these nine facilities.

Pump Motor Capacity (hp)	Pump Flow Capacity (MGD)	Pumps (Number)	Pump Driver	Backup Power Source
Active Pump Stations (4)				
40	0.29	2	Constant Speed	None
15	0.37	1	Constant Speed	None
50	0.72	3	Variable Frequency	Generator
50	1.3	2	Constant Speed	None
30	0.65	2	Variable Frequency	None
Standby or Emergency Pump Stations (5)				
20	0.23	2	Constant Speed	None
50	0.58	3	Constant Speed	None
40	1.58	1	Constant Speed	Generator
7.5	0.22	2	Constant Speed	Generator
75	1.08	3	Constant Speed	None
50	0.5	2	Constant Speed	None

Table C.34 OWD Distribution Pump Summary [OWD 1999]

Twelve storage tanks with a total capacity of 50.5 MG regulate the flow of water through the distribution system. Table C.35 describes the storage tanks used in the distribution system.

Material	Number of Tanks	Average Tank Characteristics		
		Capacity (MG)	Depth (ft.)	Diameter (ft.)
Concrete	6	5	30	168
Concrete	1	5	35.5	155
Steel	1	5	30	168
Concrete	3	3	30	130
Concrete	1	1.5	24	103

Table C.35 OWD Potable Storage Tank Summary [OWD 1999]

Electricity costs in 2003 were estimated to be $3,780 for pump stations used occasionally during periods of high demand and $65,250 to provide water to the Morro Hills area. Assuming an average cost of $0.1064 per kWh, similar to MWD, potable water distribution consumes 648 MWh each year.

C.4.2.4 Material Use Summary

Material use in the OWD system is summarized in Table C.36. The units in Table C.36 are not the same as in other material use summary tables. Because of the scale of the systems, the values have been divided by 1000.

	SUPPLY: CRA Cost (1000 1997$)	SUPPLY: CRA Weight (Mg)	SUPPLY: SWP Cost (1000 1997$)	SUPPLY: SWP Weight (Mg)	SUPPLY: San Diego Canal Cost (1000 1997$)	SUPPLY: San Diego Canal Weight (Mg)	SUPPLY: SDCWA Cost (1000 1997$)	SUPPLY: SDCWA Weight (Mg)	TREATMENT Cost (1000 1997$)	TREATMENT Weight (Mg)	DISTRIBUTION Cost (1000 1997$)	DISTRIBUTION Weight (Mg)
Mortar	$ -	-	$ -	-	$ -	-	$ -	-	$ -	-	$ 0.80	308
Metal pipe and fittings	$ -	-	$ -	-	$ -	-	$ 17,134	19,757	$ 225	193	$ 6,223	6,608
Plastic pipe	$ -	-	$ -	-	$ -	-	$ -	-	$ 112	40	$ 3,478	10,921
Concrete products	$ 12,411	152,900	$ 36,347	447,779	$ -	-	$ 21,764	236,220	$ -	-	$ 19,040	196,068
Metal valves	$ -	-	$ -	-	$ -	-	$ 43	9	$ 53	25	$ 8,189	1,107
Wood forms	$ 20,818	32,000	$ 158	243	$ 13	21	$ 12	18	$ 1,820	2,798	$ 607	933
Ready-mixed concrete	$ 46,511	1,254,686	$ 141,209	3,809,274	$17,982	485,096	$ 98	2,641	$ 4,489	121,102	$ 2,578	69,547
Reinforcing Steel	$ 44,955	91,121	$ 1,094	2,217	$ 64	130	$ 99	201	$ 4,538	9,198	$ 2,606	5,283
Steel tanks	$ -	-	$ -	-	$ -	-	$ -	-	$ 99	64	$ 523	1,059
Pumps	$ 3,438	-	$ 19,531	-	$ 600	-	$ -	-	$ -	-	$ 131	14
Metering pumps									$ 37	1	$ -	-
Precast Concrete	$ -	-	$ -	-	$ -	-	$ -	-	$ -	-	$ 4,195	12,833
Electrical	$ 95	-	$ 537	-	$ 17	-	$ 1	-	$ 45	-	$ 230	-
Controls	$ 309	-	$ 1,758	-	$ 54	-	$ 4	-	$ 148	-	$ 754	-
Measuring and metering devices	$ -	-	$ -	-	$ -	-	$ -	-	$ 3	4	$ -	-
Generators	$ -	-	$ -	-	$ -	-	$ -	-	$ -	-	$ 29	-
Adjustable frequency drives	$ -	-	$ -	-	$ -	-	$ -	-	$ -	-	$ 31	-
Landscape	$ -	-	$ -	-	$ -	-	$ -	-	$ 41	-	$ -	-
Industrial Chemicals	$ -	-	$ -	-	$ -	-	$ -	-	$ 1,354	6,335	$ -	-
Polymers	$ -	-	$ -	-	$ -	-	$ -	-	$ 400	1,165	$ -	-
Filter media, Agg	$ -	-	$ -	-	$ -	-	$ -	-	$ 26	224	$ -	-
Anthracite, filter media	$ -	-	$ -	-	$ -	-	$ -	-	$ 539	32	$ -	-
Industrial equipment	$ -	-	$ -	-	$ -	-	$ -	-	$ 935	-	$ -	-

Table 6.36 OWD Imported Water Material Use Summary

Table C.36 OWD Imported Water Material Use Summary

C.4.2.5 Construction Equipment Use Summary

Construction equipment use in the OWD system is summarized in Table C.37.

	Units	SUPPLY CRA	SWP	San Diego Canal	SDCWA	TREAT-MENT	DISTRI-BUTION
Excavator							
JD200C	hrs	30	26	-	11	50	16,846
Cat 375	hrs	242,625	1,227,526	341,240	2,842	335	194
Crane	hrs	602	1,763	-	2,842	288	3,103
Loader	hrs	66,161	698,074	371,050	6,901	205,775	8,939
Compaction							
Plate Compactor	hrs	6,233	164,932	86,789	1,427	37	2,314
Roller Compactor	hrs	-	-	-	-	31	-
Concrete placement							
Pump	hrs	937,614	59,814	7,617	41	1,902	1,092
Vibrator	hrs	38,251	89,721	11,426	62	2,852	1,638
Truck	mi	2,112,610	6,343,176	815,349	111	202,833	6,267
Off-haul dump truck	mi	46,031,966	142,223,614	17,877,778	672,694	149,650	365,692
Sludge disposal							
Loader	hrs	-	-	-	-	350	-
Dump truck	mi	-	-	-	-	110,118	-

Table C.37 OWD Imported Water Construction Equipment Use Summary

C.4.3 Desalinated Water

The remainder of the OWD's potable water (8%, about 2,700 AF per year or 2.4 MGD) is obtained from brackish groundwater treated at the Mission Basin Desalting Facility (MBDF). The facility has been expanded to be able to provide three times the current operating production. However, to date production wells in the Mission Basin aquifer have not been able to supply that quantity of influent water. Information in this section was obtained from a variety of sources [OWD 2003; OWD 2004].

C.4.3.1 Supply

An average of 3,500 AF per year (3.1 MGD) of water is obtained from three on-site wells (Wells 1, 2, and 3) and two off-site wells (Wells 4 and 5). The on-site wells are 16-in. diameter deep wells and are screened 200 ft. bgs. The off-site wells are 15.5-in. diameter shallow wells, screened 135 ft. bgs. All wells are gravel-packed with a stainless steel casing and pump column. Off-site wells are piped approximately 3 miles to the plant in 24-in. diameter mortar-lined DI pipe. The pipe is buried at 3 ft. bgs and has 12 fittings. Isolation valves and pressure regulating valves are located at the pump intake facilities for each well. The off-site wellheads are housed in a 300 ft^2 building.

In addition, to monitor the status of the Mission Basin aquifer, three monitoring wells have been installed. Two are deep aquifer monitoring wells (200 ft. bgs) and one is shallow (135 ft. bgs). The three wells are PVC-screened and assumed to be 2-in. diameter.

Each on-site well contains a 60-hp submersible pump. The off-site wells and supply pipeline uses four 75-hp pumps. An estimated 860 MWh are consumed annually to operate these pumps.

C.4.3.2 Treatment

The Mission Basin Desalting Facility (MBDF) is located in the city of Oceanside. The plant produces a total of 2,900 AF (2.6 MGD) of potable water each year. The treatment process description follows.

Figure C.15 shows the treatment process. A 2,500 ft^2 administrative building and 3,000 ft^2 warehouse are located at the plant site.

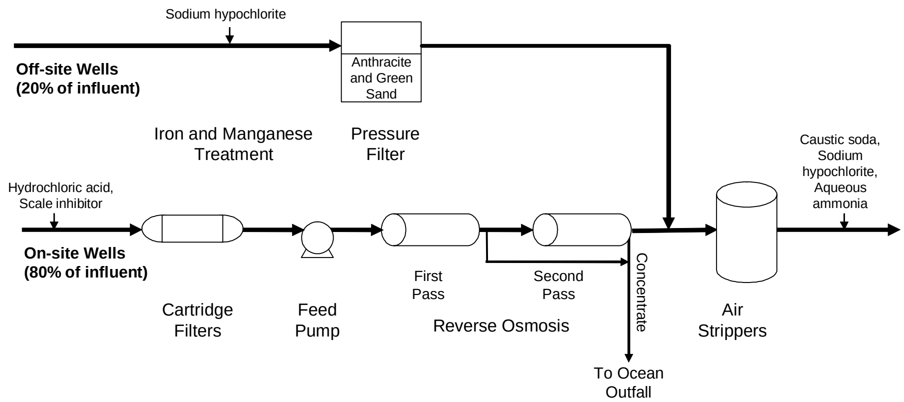


Figure C.15 Mission Basin Desalting Treatment Schematic

Eighty percent of influent water (2,800 AF each year or 2.5 MGD) comes from on-site wells; the remainder is from off-site wells. Water from on-site and off-site wells are processed through separate treatment trains to optimize treatment energy consumption and achieve effluent regulatory standards.

Water from the on-site wells is processed through the RO plant. On-site well influent is pretreated; the pH is adjusted using hydrochloric acid and a scale inhibitor is added. Water passes through a series of three 1-micron cartridge filters prior to entering the RO process. These are replaced approximately once a month. The MBDF uses a two-pass RO process comprised of 48 Hydronautics vessels in each of two treatment trains. Each vessel contains 7 membranes; 336 membranes comprise each train. Thirty-two membranes are utilized in the first pass. The brine from the first pass is then sent through the remaining 16 membranes. Currently only one treatment train is operating.

The pressure in the membranes is raised by approximately 120 psi using two 250-hp pumps. Each pump has an associate variable speed drive to control its operation. The RO process produces 75% useable product water (2,200 AF annually or 2.0 MGD) and 25% concentrated brine (620 AF annually 0r 0.6 MGD). The product water, or permeate, from the RO process is blended with the off-site water at a 4:1 ratio.

Prior to blending, influent from off-site wells is treated to achieve regulatory standards in the blended water. The primary goal of this treatment is to reduce metals concentrations. Filtered water is treated with sodium hypochlorite to precipitate iron and then filtered.

Off-site water is filtered by a pressure filter comprised of green sand and anthracite. Two filters are located at the plant – one in operation and one on stand-by at a given time. Each filter has a surface area of 350 ft2 and contains 2 ft. of sand. Filter dimensions are estimated based on industry standards and a design flow rate of 6 gal/min-ft^2 [ASCE 1998]. The filter is housed in a steel tank. Filtered water is blended with RO product water prior to decarbonation.

The blended water is decarbonated in three air strippers filled with plastic spherical packing material. The air strippers are assumed to be housed in 2,000-gal. steel tanks. The air strippers off-gas CO_2; the CO_2 emissions are not tracked because the air permit does not require it. These CO_2 emissions are not included in the inventory. Caustic soda is added to the blended water to raise the pH. Finally, decarbonated water is disinfected using a combination of sodium hypochlorite and aqueous ammonia prior to entering the distribution system.

Chemical use is summarized in Table C.38. The chemicals are assumed to be housed in five 2,000-gal. tanks.

Chemical	Use	Annual Volume Consumed (lb)
Hydrochloric acid	pH control	470,000
Proprietary	Scale inhibitor	22,000
Caustic soda	pH control	120,500
Sodium hypochlorite	Disinfectant	83,400
Aqueous ammonia	Disinfectant	99,400

Table C.38 MBDF Chemical Use [OWD 2003]

Brine from the RO process is combined with effluent from the San Luis Rey WWTP and transported to the Pacific Ocean via an existing outfall. The construction of the outfall is excluded from the analysis.

The off-site water filter is backwashed approximately every 72 hours using a solution of sodium hypochlorite. Backwash water is discharged to the sewer.

The chemical distribution system includes two 0.75-hp pumps, six 0.33-hp pumps, a 0.5-hp pump, and a 2-hp pump. In addition, the sewer system contains a 7.5-hp grinder pump and 40-hp membrane cleaning pump. A 5-hp air compressor is used for iron and manganese removal; three 7.5-hp blowers are also used for air strippers.

The MBDF used $848,450 in electricity in 2003, including both supply and treatment. Assuming an electricity cost similar to MWD of $0.1064, the MBDF uses an estimated 8,000 MWh each year [MWD 2004]. Approximately 7,140 MWh are used in the treatment phase of desalinated water production.

C.4.3.3 Distribution

The desalinated water is distributed using the potable water distribution system described in Section C.4.2.3. All facilities are accounted for in that analysis.

C.4.3.4 Material Use Summary

Table C.39 summarizes material use in the system. Material service lives are assumed to be the default values listed in Table 5.1.

	SUPPLY		TREATMENT	
	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)
Mortar	$ 80	171,000	$ -	-
Metal pipe and fittings	$891,000	728,000	$ 23,800	22,130
Plastic pipe	$ 580	-	$ 21,200	7,590
Metal valves	$ 14,400	1,120	$ 9,700	4,090
Ready-mixed concrete	$ 4,330	67,300	$ 58,900	1,589,000
Steel	$ 4,370	405,000	$ 59,500	12,190,000
Pumps	$ 53,100	870	$ 44,900	360
Metering pumps	$ -	-	$ 1,900	340
Electrical	$ 1,900	-	$ 8,550	-
Controls	$ 6,140	-	$ 28,000	-
Measuring and metering devices	$ 1,710	180	$ 1,030	110
Landscaping	$ -	-	$ 7,780	-
Aggregate	$ 1,350	3,520,000	$ -	-
Tanks	$ -	-	$ 33,800	25,400
Industrial Chemicals	$ -	-	$ 40,500	351,000
Chems and preps	$ -	-	$ 20,100	9,980
Aggregate filter media	$ -	-	$ 37,800	34,930
RO membranes	$ -	-	$ 136,000	-
Filter membranes	$ -	-	$ 270	-
Steel filter casing	$ -	-	$ 90	-
Industrial equipment	$ -	-	$ 50,000	-
Blowers	$ -	-	$ 1,600	50
Air compressors	$ -	-	$ 2,260	60
Adjustable frequency drives	$ -	-	$ 50,000	-

Table C.39 MBDF Material Use Summary

Delivery distances for materials delivered less than 50 miles were multiplied by 200% for CRA materials and 150% for SWP to account for the remote location of much of the infrastructure.

C.4.3.5 Construction Equipment Use Summary

Table C.40 summarizes the construction equipment use associated with MBDF. Construction equipment use occurs only at the initial phase of the project.

	Units	SUPPLY	TREATMENT
Excavator			
JD200C	hrs	107	10
Cat 375	hrs	0	0
Crane	hrs	106	23
Loader	hrs	87	6
Plate compactor	hrs	20	1
Concrete placement			
Pump	hrs	2	25
Vibrator	hrs	3	37
Truck	mi	196	2,661
Off-haul dump truck	mi	5,829	1,412

Table C.40 MBDF Construction Equipment Use Summary

C.4.4 Recycled Water

In addition, each year approximately 80 AF of non-potable water (0.1 MGD or less than 1% of total supply) is supplied by recycled water from the San Luis Rey wastewater treatment plant (SLR) owned and operated by the city. The SLR plant currently treats 12,000 Af per year (10.7 MGD) and will be expanded to 19,500 AF each year (17.4 MGD). In the future, the recycled water plant may be expanded to provide 5 MGD for reuse and up to 2.5 MGD for aquifer recharge. However, due to the unfavorable economics of distribution, it is unlikely the system will be expanded to be a significant source of supply.

C.4.4.1 Supply

The recycled water plant is located on the SLR site. It is assumed that 500 ft. of 6-in. PVC piping was installed 4 ft. bgs to connect the two plants. Four fittings and one isolation valve are also included. A 10-hp pump and one pressure regulating valve is required to transport water into the package plant. Moving water between the plants requires an estimated 25 MWh per year.

C.4.4.2 Treatment

The secondarily-treated effluent from SLR is processed through a DynaFlow package plant. The package plant consists primarily of a sand filter. Based on typical industry requirements and a design flow rate of 4 gal/min-ft^2, two 10 ft^2 filters were constructed. One filter is in operation at a time. The filters contain 18 in. of sand and 12 in. of support gravel. Treated water is stored in a concrete basin prior to distribution. The basin is 2,000 ft^2 and 3 ft deep. No chemicals are added to the water.

Filters are backwashed daily. Backwash water is assumed to be processed with the sludge at the adjacent WWTP and is not included in the assessment.

Electricity use in the system is nominal and is estimated to be 15 MWh per year. A 400 ft^2 building was constructed to house an office and laboratory area.

C.4.4.3 Distribution

The recycled water is pumped approximately 2 miles to Oceanside Municipal Golf Course for irrigation and to Whelan Lake for maintenance water. The distribution system includes 11,134 ft. of pipe, assumed to be 6-in. PVC with 21 fittings. All pipe is assumed to be buried 3 ft. bgs. The distribution system also includes one blow-off valve, two air vents, and three isolation valves. Four underground vaults are necessary to house the valves. The distribution system has no storage tanks.

The SLR is located near sea level so all water distributed must be pumped. Water is assumed to be pumped using one 50-hp pump which is located at the treatment plant. A pressure regulating valve is located at the pumping facility. Energy used for pumping is estimated at 130 MWh per year.

C.4.4.4 Material Use Summary

Table C.41 presents a summary of material use in the recycled water system. The costs represent initial purchase cost.

	SUPPLY		TREATMENT		DISTRIBUTION	
	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)	Cost (1997$)	Weight (kg)
Metal pipe and fittings	$ 640	150	$ 110	100	$ 3,350	760
Plastic pipe	$ 2,680	-	$ 100	40	$ 59,700	138,200
Metal valves	$ 870	70	$ 330	50	$ 2,620	220
Wood forms	$ -	-	$ 8,850	13,610	$ -	-
Ready-mixed concrete	$ -	-	$ 16,500	445,000	$ -	-
Steel	$ -	-	$ 16,700	30,000	$ -	-
Pumps	$ 3,500	80	$ -	-	$ 6,580	110
Precast concrete	$ -	-	$ -	-	$ 3,150	7,150
Electrical	$ 130	-	$ 40	-	$ 250	-
Controls	$ 420	-	$ 130	-	$ 830	-
Measuring and metering devices	$ 340	40	$ 340	40	$ -	-
Landscaping	$ -	-	$ 40	-	$ -	-
Aggregate filter media	$ -	-	$ 830	1,290	$ -	-

Table C.41 OWD Recycled Water Material Use Summary

C.4.4.5 Construction Equipment Use Summary

Table C.42 presents a summary of construction equipment use for the recycled water system.

	Units	SUPPLY	TREATMENT	DISTRIBUTION
Excavator				
JD200C	hrs	3	6	62
Loader	hrs	1	1	26
Plate compactor	hrs	-	-	8
Concrete placement				
Pump	hrs	-	7	-
Vibrator	hrs	-	10	-
Truck	mi	-	745	-
Soil Off-haul				
Dump Truck	mi	11	537	268

Table C.42 OWD Recycled Water Construction Equipment Use Summary

C.4.5 Electricity Use Summary

Table C.43 summarizes electricity used to supply water to the OWD. For imported supply, the electricity consumption shown in the table represents only the share of total consumption which is allocated to the OWD based proportionally on water provision. Most electricity use was estimated based on specific information provided by the appropriate utility. When estimates were made based on pump capacities (see Section C.2.3), the assumptions used are listed in the table.

Water Supply Phase	Pump Motor Rating (hp)	Pump Use (hrs)	Electricity Consumption (MWh)
Imported Water			
Supply	--	--	76,090
Treatment	--	--	800
Distribution	--	--	648
Recycled Water			
Supply	10	3,843	25
Treatment	--	--	5
Distribution	50	3,843	130
Desalinated Water			
Supply	420	3,843	680
Treatment	--	--	7,140
Distribution	--	--	648

Table C.43 System Electricity Use (estimated from [OWD 2003])

C.5 References

[ADA 2004]. "The Fluoride Debate" home page. American Dental Association. http://www.fluoridedebate.com. (Accessed February 26, 2004.)

[ASCE 1998]. *Water Treatment Plant Design*. 3rd ed. American Society of Civil Engineers and American Water Works Association. McGraw-Hill: New York. 1998.

[Cape Canaveral 2004]. "Corrosion Control" home page. Cape Canaveral Water Treatment Plant. http://www.geocities.com/CapeCanaveral/3000/znpo4.htm (Accessed February 26, 2004.)

[Dams 2004]. "California Dams" home page. University of California Regents. http://countingcalifornia.cdlib.org/pdfdata/csa02/G03 (Accessed April 27, 2004.)

[DVL 2004]. "The Construction of Diamond Valley Lake" home page. Metropolitan Water District of Southern California. http://www.dvlake.com/general_info11.html (Accessed March 12, 2004.)

[Gleick 2003]. Gleick, P.H., "Water Use." *Annual Review of Environment and Resources*, 1994. 28: 275-314.

[Huffman 2001]. Huffman, J. "Water Supply Planning: Marin Municipal Utility District." Presented to Marin Countywide Plan Working Group on November 6, 2001. http://www.future-marin.org/library.cfm?element=5#Reports (Accessed March 25, 2003.)

[Jeane 2004]. Jeane, P. Personal communication (electronic mail). Sonoma County Water Agency. February 13 and 23, 2004.

[Joe 2004]. Joe, J. Personal communication (electronic mail). Las Gallinas Valley Sanitation District. February 26 and 27, 2004.

[Junnila 2003]. Junnila, S. and A. Horvath. "Life-Cycle Environmental Effects of an Office Building." *Journal of Infrastructure Systems*. **9**(4): 10, 2003.

[Kauwe 2004]. Kauwe, J. Personal communication (electronic mail). North Marin Water District. February 25, 2004.

[LGVSD 2004]. "Treatment and Reclamation" home page. Las Gallinas Valley Sanitation District. http://www.lgvsd.org. (Accessed February 16, 2004.)

[Mays 2000]. Mays, L.W., ed. *Water Distribution Systems Handbook*. American Water Works Association, McGraw-Hill: London. 2000.

[MBK 2002]. MBK Engineers, *Marin Municipal Water District Water Supply Planning Model*, Sacramento, California, August 2002.

[Means 1997]. Page, J., ed. *Heavy Construction Cost Data*, 12th ed. R.S. Means Corporation: Kingston, MA, 1997.

[MMWD 1990]. *Why Desalination May Be Our Best Water Supply Option*. Marin Municipal Water District: Corte Madera, California, 1990.

[MMWD 1995]. *Urban Water Management Plan*. Marin Municipal Water District: Corte Madera, California, December 1995.

[MMWD 2001]. "Electricity Moves Water" in *On the Waterfront*. Marin Municipal Water District: Corte Madera, California, July/August 2001. http://www.marinwater.org/owf7801.pdf (Accessed April 13, 2004).

[MMWD 2003]. *Long-Range Capital Plan, 2003-2013- Draft*. Marin Municipal Water District: Corte Madera, California, September 2003.

[MMWD 2004]. "Marin Municipal Water District" home page, http://www.marinwater.org. (Accessed January 12, 2004.)

[MUWMP 2003]. *Draft Urban Water Management Plan 2000*. Marin Municipal Water District: Corte Madera, California, February, 2003.

[MWD 1996]. *Southern California's Integrated Water Resources Plan*. Metropolitan Water District of Southern California: Los Angeles, California, 1996.

[MWD 2000]. *The Regional Urban Water Management Plan*. Metropolitan Water District of Southern California: Los Angeles, California, December 2000.

[MWD 2004]. "The Metropolitan Water District of Southern California" home page. http://www.mwdh2o.com (Accessed March 2, 2004.)

[Nayyar 2002]. Nayyar, M.L., *Piping Databook*. McGraw-Hill: New York, 2002.

[NMWD 2004]. "North Marin Water District" home page. http://www.nmwd.org. (Accessed February 20, 2004.)

[OWD 1999]. *Water Master Plan*. ASL Consulting Engineers for Oceanside Water Utilities Department: Oceanside, California., May 1999.

[OWD 2001]. *City of Oceanside 2000 Urban Water Management Plan*. Oceanside Water Utilities Department: Oceanside, California, 2001.

[OWD 2003]. Site visit to Oceanside Water Utilities Department, Oceanside, California. August 6-8, 2003.

[OWD 2004]. Tucker, S. Personal communication (electronic mail). Oceanside Water Utilities District. March 24-31, 2004.

[Parker Dam 2004]. "The Colorado River: Parker Dam" home page. Desert USA. http://www.desertusa.com/colorado/parker_dam/du_parkerdam.html (Accessed March 20, 2004.)

[Peters 2003]. Peters, M.S.; Timmerhaus, K.D.; West, R. *Plant Design and Economics for Chemical Engineers*. 5th ed. McGraw-Hill: New York, 2003.

[SCWA 2004]. "Sonoma County Water Agency" home page. http://www.scwa.ca.gov/ (Accessed March 4, 2004.)

[SDCWA 2002]. *Regional Water Facilities Master Plan- Draft.* San Diego County Water Authority; San Diego, California. December 2002.

[SDCWA 2003]. Nakamura, J., Engineering Department, San Diego County Water Authority. Personal Communication (site visit). San Diego, California. August 7, 2003.

[Sheikh 2001]. Sheikh, B. and Parsons Engineering Corporation. "Seawater Desalination as a Possible Alternative Component of Integrated Water Resources" for Marin Municipal Water District. June 2001.

[Stokes 2004]. Stokes, J. "Life-cycle Assessment of Alternative Water Supply Systems in California." Ph.D. Dissertation. University of California, Berkeley, 2004.

[SWP 2002]. *Management of the California State Water Project*. Report 132-01. California Department of Water Resources: Sacramento, California, 2002.

[Temecula 2004]. "Diamond Valley Lake" home page. City of Temecula. http://www.oldtemecula.com/lakes/reservoir.html (Accessed March 20, 2004.)

[Theisen 2004]. Theisen, Ron. Personal Communication. General Manager, Marin Municipal Utility District: Corte Madera, California, February 2004.

[URS 2003]. URS Corporation. *Initial Project Screening and Environmental Screening- MMWD Desalination Project*, Oakland, California. May 2003.

[USBR 2004]. "Dams, Projects, and Powerplants" home page. U.S. Bureau of Reclamation: Washington, D.C. http://www.usbr.gov/dataweb/dams/ca00223.htm (Accessed March 22, 2004.)

[Wilkinson 2004]. Wilkinson, R. "Methodology for Analysis of the Energy Intensity of California Water Systems." Report to Lawrence Berkeley Laboratory. January 2000. http://www.es.ucsb.edu/faculty/Wilkinson_EWRPT01%20DOC.pdf (Accessed May 16, 2004.)

[World Climate 2004]. "Oceanside, California, USA Average Rainfall" home page. World Climate. http://www.worldclimate.com/cgi-bin/data.pl?ref=N33W117+2200+046378C (Accessed February 17, 2004.)

Appendix D. Data

NOTE: The text in this Appendix is quoted from Dr. Stokes's PhD dissertation [Stokes 2004].

D. 1 Emission Factors

D.1.1 EIO-LCA Emission Factors

Source: [CMU 2004]

For complete descriptions of sectors http://www.eiolca.net/sectors.html

Impacts:	Energy	CO	NO_2	PM10	SO_2	CO_2	VOC	GWP
EIO-LCA item	**MJ/1997$**	**g/1997$**	**g/1997$**	**g/1997$**	**g/1997$**	**g/1997$**	**g/1997$**	**g/1997$**
Adhesives and sealants	15.53	3.92	3.62	0.64	2.85	922.76	1.41	1016.61
Asbestos products	6.45	1.63	2.87	1.22	2.55	303.78	5.69	323.85
Asphalt paving mixtures and blocks	77.47	6.41	5.77	3.12	5.90	7203.00	2.21	8028.36
Blast furnaces & steel mills	31.55	19.11	5.93	1.58	8.80	1999.93	1.18	2179.93
Blowers and fans	6.99	3.75	1.64	0.34	1.97	450.60	1.48	498.05
Brick and structural clay tile	52.94	8.46	7.15	3.00	11.70	3689.09	1.28	4130.46
Celluosic manmade fibers	41.53	6.34	10.01	1.64	12.26	2350.73	7.53	2569.41
Chems and chem preparations, n.e.c.	20.05	6.15	4.89	1.76	3.61	1200.34	2.03	1361.72
Clay refractories	33.81	8.27	8.95	2.58	9.38	2347.82	1.88	2641.60
Coal	11.79	2.36	3.30	1.13	3.11	831.05	0.52	4285.32
Concrete block and brick	27.25	6.08	10.51	2.08	9.16	1922.23	1.23	2170.62
Concrete products, except block and brick	14.52	4.31	6.62	1.28	5.79	1005.21	0.88	1115.65
Construction equipment and machinery	7.74	3.88	2.10	0.43	2.35	506.38	0.65	558.46
Crude Petroleum and Natural Gas	9.81	3.33	6.83	1.05	4.60	627.77	1.57	694.89
electric lamp bulbs and tubes	7.51	1.62	2.05	0.33	1.81	495.83	0.82	549.79
electrical industrial apparatus, n.e.c.	8.47	2.96	2.82	0.48	2.17	573.33	0.70	634.49
Electrical machinery, equipment, and supplies	7.49	2.42	2.00	0.35	2.60	511.62	0.67	577.58
Electronic computers	6.03	1.85	1.69	0.28	1.95	424.86	0.43	479.43
Fabricated rubber products, n.e.c.								
Fluid power equipment	7.22	0.48	1.73	0.37	2.15	477.22	0.70	530.03
Gaskets, packing, and sealing devices	11.04	3.84	2.27	0.38	2.24	648.25	1.13	712.82
general ind machinery and equip n.e.c.	6.00	2.73	1.46	0.32	1.72	394.92	0.46	435.92
Glass and glass products, except containers	17.22	2.31	6.00	0.93	3.25	1185.70	0.91	1308.93
Highways and streets	12.82	4.63	4.92	3.36	2.81	972.37	0.83	1086.75
Ind and commercial mach and equip, n.e.c.	5.91	2.48	1.40	0.31	1.97	389.69	0.33	429.99
Industrial inorganic & organic chemicals	27.39	5.22	5.98	1.16	6.02	1575.00	2.32	1763.41
Industrial trucks and tractors	8.38	4.87	2.23	0.43	2.25	547.02	0.81	604.48
Iron and steel forgings	15.35	5.87	3.42	0.63	4.27	972.18	0.72	1065.80
lab apparatus and furniture	5.28	2.08	1.39	0.28	1.39	351.29	0.59	387.59

EIO-LCA item (Impacts:)	Energy MJ/1997$	CO g/1997$	NO_2 g/1997$	PM10 g/1997$	SO_2 g/1997$	CO_2 g/1997$	VOC g/1997$	GWP g/1997$
Landscape and horticultural services	7.22	3.22	6.55	7.18	1.57	457.52	1.04	512.12
Lighting fixtures and equipment	8.07	3.38	2.18	0.38	2.19	518.21	0.70	572.61
Lime	68.86	13.11	22.28	5.97	20.12	4811.01	0.99	5283.79
Maintenance and repair of buildings	7.13	4.12	3.73	5.47	1.90	483.55	0.60	541.46
Maintenance and repair of highways and streets	11.52	4.29	4.55	5.41	2.11	890.16	0.75	992.82
Manmade organic fibers, except cellulosic	22.90	3.97	4.75	1.55	5.35	1333.90	2.68	1485.05
measuring and dispensing pumps	6.97	3.39	1.74	0.32	2.07	453.51	0.55	499.72
Mechanical and measuring devices	6.52	2.30	1.65	0.30	2.74	455.64	0.42	514.10
metal doors, sash, frames, molding, and trim	9.09	6.92	2.51	0.52	3.73	556.68	0.82	615.38
metal pipe, valves, and fittings	8.61	4.04	2.04	0.49	2.73	553.84	0.52	611.38
Misc plastic products, n.e.c.	11.21	2.93	3.14	0.48	2.81	722.44	1.38	800.58
Motors and generators	8.25	3.87	2.13	0.43	2.53	537.65	0.65	593.33
Office equipment, n.e.c.	8.13	2.55	2.26	0.36	2.35	551.90	0.79	622.96
Office furntiure, non-wood	12.43	4.73	3.13	0.69	3.47	821.78	1.73	927.66
Office, industrial, comm buildings	7.85	4.18	3.50	4.13	2.19	530.02	0.67	595.02
Paperboard containers & boxes	16.78	6.56	5.14	0.97	5.12	1109.86	1.77	1220.86
Petroleum refining	21.77	5.22	6.88	1.17	6.23	1236.42	2.59	1315.59
Plastic materials and resins	22.42	3.96	4.60	0.79	4.41	1285.59	2.08	1415.29
Pumps and compressors	6.30	3.47	1.57	0.33	1.77	409.96	0.46	454.41
Ready-mixed concrete	19.06	5.43	9.85	1.91	8.08	1318.80	1.11	1460.26
Relays and industrial controls	6.99	2.97	1.82	0.33	2.22	472.60	0.58	532.74
Rubber and plastics hose and belting	13.59	15.79	2.70	0.69	3.36	788.49	1.68	866.98
Sand and Gravel	15.45	1.74	2.70	3.03	3.15	1094.22	0.46	1201.69
Sawmills & planing mills, general	7.34	4.95	3.30	1.33	1.57	467.81	1.26	519.00
Special industry machines, n.e.c.	6.33	2.91	1.69	0.35	1.93	418.85	0.48	462.80
Steel wire drawing, spikes, and nails	24.15	13.52	6.27	1.22	7.59	1622.35	1.32	1875.05
Switchgear and switchboard apparatus	8.27	3.15	2.10	0.38	2.77	554.61	0.48	625.49
Synthetic rubber	30.81	7.91	4.68	0.72	4.73	1744.14	3.17	1913.95
Turbine and turbine generator sets	6.14	3.03	1.57	0.36	1.73	404.00	0.52	447.45
Wiring devices	11.36	4.25	2.71	0.51	3.73	750.14	0.71	845.41
Wood office furniture	11.13	3.57	3.16	0.81	2.99	754.92	3.09	854.99

The following sector was for demand management analysis- NOT IN WEST TOOL

EIO-LCA item (Impacts:)	Energy MJ/1997$	CO g/1997$	NO_2 g/1997$	PM10 g/1997$	SO_2 g/1997$	CO_2 g/1997$	VOC g/1997$	GWP g/1997$
household laundry equipment	9.67	4.42	2.41	0.47	2.64	618.15	1.21	682.15

D.1.2 Construction Cost Index Values

Year	CCI
1987	410
1988	421
1989	430
1990	441
1991	450
1992	464
1993	485
1994	504
1995	509
1996	523
1997	542
1998	551
1999	564
2000	579
2001	591
2002	604

Source: ENR 2004; Peters 2003

D.1.3 Transport Emission Factors

Sources for all emission factors listed after the appropriate table.

D.1.3.1 Aircraft Emission Factors

AIRCRAFT CALCULATIONS

Dedicated-Freighter Aircraft: Freight Capacity

	Freight Capacity (kg)	Freight Capacity (cu feet)	
B757-200 Freighter	39,780	8,430	http://www.boeing.com/commercial/757family/pf/pf_200f_tech.html

Sources

Cargo & passenger capacity for all models except A310, A330 & A340 are averages according to Air Transport Association, ATA Annual Report 2001 (ATA). Aircraft Operating Statistics—2000,
Available at http://www.airlines.org/public/industry/bin/2001Aircraft.pdf

AIRCRAFT LANDING/TAKE-OFF CYCLE (LTO)

	Fuel Consumption	Emission Factors Kg/LTO							
	(kg/LTO)	PM	SO_2	CO	NO_x	CH_4	CO_2	NMVOC	N_2O
B757	1300	0.5	1.3	10.6	21.6	0.10	4110	0.8	0.1

Notes: One LTO per roundtrip * No data were available for the submodels (except A319 capacities), so data for the primary model were used except for passenger capacity.

Sources:

1. Fuel consumption and emission data (except PM) for all aircraft (except A330, A340 and B777) are from "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual" http://www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch1ref7.
2. Fuel consumption and emission data (except PM) for A330, A340, B777 are from Atmospheric emission inventory guidebook. Vol. 2. (European Environment Agency, Copenhagen, 1996) p. B851/21
Group 8 Other mobile sources and machinery: Table 8.3 See http://reports.eea.eu.int/EMEPCORINAIR/en/page017.html
3. PM data for all aircraft except A330, A340 and B777 are from Table VII, in Romano, Gaudioso, R. De Lauretis. 1999. Aircraft Emissions: A Comparison Of Methodologies Based On Different Data Availability.
Environmental Monitoring and Assessment 56: 51–74. Available on http://147.46.94.112/e_journals/pdf_full/journal_e/e15_9956103.pdf

AIRCRAFT CRUISE CYCLE

This section provides emission factors, fuel usage, cruise speed, passenger and cargo capacities to calculate aircraft emissions during their cruise cycle.

SO_2 & CO_2 Emission Factors	Fuel Usage *total of all engines* (kg/hour)	Cruise Speed @35k ft (mph)	Fuel Usage (kg per mile)	Engine Type [N1]	Jet Fuel Emission Factors					Airplane Emission Factors (g/mile) = Fuel Efficiency (kg / hr) / Cruise Speed (miles /hr) * Jet Fuel Emission Factor (g/kg)				
					SO_2	CO	HC	NO_x	CO_2	SO_2	CO	HC	NO_x	CO_2
					Kg/Kg	g/Kg	g/Kg	g/Kg	Kg/Kg	g/mile	g/mile	g/mile	g/mile	g/mile
B757	3167	464	6.83	jt8d-17	0.001	1.6	0.3	9.05	3.150	6.83	10.92	2.05	61.77	21,501

Notes: The only data from this table used in our calculations are the SO_2 and CO_2 jet fuel emission factors. More precise data for CO, HC, and NOx emissions are provided in the tables below.

[N1] Jet Fuel Emission Factors correspond to engine types. For A320, B727-B767, DC9, DC10, F100, L1011, we used the same assumptions as the UC Berkeley Telework project regarding which engines are typically mounted on which aircraft

Sources: Fuel Usage (except A310, A330, A340) US averages reported in gallons/hour by Air Transport Association, ATA Annual Report 2001 (ATA). Aircraft Operating Statistics—2000, Available at http://www.airlines.org/public/industry/bin/2001Aircraft.pdf
Converted to kg/hour using 1 gal/hr = 2.96 kg/hr because kerosene is 783 kg/m3, 1 gal = 3.785 L , 1 m3=1000L . Thus 1 gal/hr * 783 kg/m3 * 3.785 L/gal * 0.001 m3/L = 2.96 kg/hr.
Conversion data source: Intergovernmental Panel on Climate Change (IPCC). 1999. Aviation and the Global Atmosphere, Section 7.8. Aviation Fuels, http://www.grida.no/climate/ipcc/aviation/109.htm

2. Cruise speed (except A310, A330, A340): Averages according to Air Transport Association, ATA Annual Report 2001 (ATA). Aircraft Operating Statistics—2000, http://www.airlines.org/public/industry/bin/2001Aircraft.pdf Also, see sources of technical specifications (above) and ATA

3. SO_2 and CO_2 emission factors: Table VI-b, Romano et al. Their "Simple" Method reported SO_2 ad CO_2 emission factors for all aircraft types as 1 and 3150, respectively. CO, HC, NOx emission factors: Table IV, Romano et al.

AIRCRAFT CRUISE CYCLE: Fuel Use Table

	Flight Distance in Miles									
Fuel Use (g/mile)	**0**	**250**	**500**	**750**	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**
B757	9359.2	8628.7	7634.7	7295.2	7137.7	7061.8	7077.0	7109.2		

Notes First data column corresponds to 125 miles, but we assume it applies to all flights below 250 miles

Source European Environmental Agency, UNECE/EMEP Task Force on Emissions Inventories and Projections. 2001. EMEP/CORINAIR Emission Inventory Guidebook - 3rd edition.
Technical report No 30. Copenhagen: European Environmental Agency.
http://reports.eea.eu.int/technical_report_2001_3/en/en
Group 8: Other mobile sources and machinery. B851 Spreadsheet 1
http://reports.eea.eu.int/technical_report_2001_3/en/B851vs2.3spreadsheet1.pdf

AIRCRAFT CRUISE CYCLE: SO_2 Table

This table calculates SO_2 emissions by multiplying the SO_2 fuel emission factor from the "SO_2 & CO_2 Emission Factors" table above by the "Fuel Use Table"

	Flight Distance in Miles									
SO_2 emissions (g/	**0**	**250**	**500**	**750**	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**
B757	9.4	8.6	7.6	7.3	7.1	7.1	7.1	7.1		

Notes & Sources: Calculation is Emission Factor (Kg CO_2/Kg Fuel) * Fuel Consumption (g/mile) = CO_2 Emissions in g/mile
See notes and sources for "SO_2 & CO_2 Emission Factors" table and "Fuel Use Table"

AIRCRAFT CRUISE CYCLE: CO_2 Table

This table calculates CO_2 emissions by multiplying the CO_2 fuel emission factor from the "SO_2 & CO_2 Emission Factors" table above by the "Fuel Use Table"

	Flight Distance in Miles									
CO_2 emissions (g/	**0**	**250**	**500**	**750**	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**
B757	29481	27180	24049	22980	22484	22245	22293	22394		

Notes & Sources: Calculation is Emission Factor (Kg CO_2/Kg Fuel) * Fuel Consumption (g/mile) = CO_2 Emissions in g/mile
See notes and sources for "SO_2 & CO_2 Emission Factors" table and "Fuel Use Table"

Aircraft

Data Sources

Romano D., D. Gaudioso, R. De Lauretis. 1999. Aircraft Emissions: A Comparison Of Methodologies Based On Different Data Availability.
Environmental Monitoring and Assessment 56: 51–74. Available on
http://147.46.94.112/e_journals/pdf_full/journal_e/e15_9956103.pdf
also available here: http://digilander.iol.it/unicomal/upload/AIRCRAFT%20EMISSIONS-ENEA.htm Accessed January 25, 2002.

Sorensen L., N. Kilde. Risoe National Laboratory, Systems Analysis Department. Waste Treatment and Disposal: Air Traffic. October 1995.
http://eionet.eea.eu.int/aegb/cap08/b851.htm, Accessed January 25, 2002
Published here: Sørensen, L.; Kilde, N.A., Air traffic. Chapter 18-19. In: Atmospheric emission inventory guidebook. Vol. 2. (European Environment Agency, Copenhagen, 1996) p. B851/21
http://reports.eea.eu.int/EMEPCORINAIR/en/page017.html

European Environmental Agency, UNECE/EMEP Task Force on Emissions Inventories and Projections. 2001. EMEP/CORINAIR Emission Inventory Guidebook - 3rd edition.
Technical report No 30. Copenhagen: European Environmental Agency.
http://reports.eea.eu.int/technical_report_2001_3/en/en
Group 8: Other mobile sources and machinery. B851 Spreadsheet 1
http://reports.eea.eu.int/technical_report_2001_3/en/B851vs2.3spreadsheet1.pdf
Used CO, HC, and NOx data for aircraft cruise cycle emission factors

Air Transport Association, ATA Annual Report 2001 (ATA). Aircraft Operating Statistics—2000, Figures are averages for most commonly used models
http://www.airlines.org/public/industry/bin/2001Aircraft.pdf
Used aircraft passenger seats, fuel consumption, and cruise speed data

Intergovernmental Panel on Climate Change (IPCC). 1999. Aviation and the Global Atmosphere
http://www.grida.no/climate/ipcc/aviation/index.htm
Technical specification sources:
Boeing
Freighters: http://www.boeing.com/news/releases/2000/news_release_000928a.html
Cargo capacity of freight models: http://www.mairon.com/english/flugtyp.htm
B747 Freighter: http://www.boeing.com/commercial/747family/pf/pf_400f_back.html
Cruise Speed data from Boeing, Commercial Plane Information. Product Info. Technical Specs.
Boeing Commercial Plane Information. Product Info. Technical Specs. http://www.boeing.com/commercial/flash.html

B757 & L1011 cruise speed in mph http://www.ual.com/site/primary/0,10017,2490,00.html accesssed Mar 18, 2002.

ADDITIONAL SOURCES
Technical Review: Aviation Fuels. Chevron Products Company. 2000
Available at http://www.chevron.com/prodserv/fuels/bulletin/aviationfuel/pdfs/aviation_fuels.pdf

Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft. US EPA. 1999
Report EPA420-R-99-013 Available at http://www.epa.gov/otaq/regs/nonroad/aviation/r99013.pdf

Indicators of the Environmental Impacts of Transportation: Highway, Rail, Aviation, and Maritime Transport. US EPA.
Report EPA 230-R-96-009. Available at http://www.epa.gov/OMS/transp/96indict.pdf

Calculation: Cargo **Airplane** emissions per kg **cargo** are calculated as follows:
{LTO Emissions (kg/LTO) * 1000 g/kg + Distance Traveled (miles) * Airplane Emission Factor (g/mile) } * {Cargo

D.1.3.2 Other Transport Emissions

Source: [OECD 1997]

Cargo Emissions (non-Aircraft)

	Emission factors in grams/kg/mi								Fuel Consumption
	PM	SO2	CO	HC*	NOx **	CO2	NMVOC	VOC	gal/kg/mile
Local Trucl	9.66E-04	6.04E-04	3.30E-03	2.27E-03	7.85E-03	5.68E-01			5.65E-05
Long-Dista	3.02E-04	2.29E-04	5.55E-04	5.47E-04	3.89E-03	2.08E-01			2.07E-05
Ship	7.24E-05	8.05E-04	1.81E-04	1.02E-04	5.69E-04	5.63E-02		1.61E-04	5.61E-06
Train	9.25E-05	2.31E-04	1.38E-04	7.40E-05	7.76E-04	9.62E-02		1.29E-04	9.57E-06

Airplane is assumed to be a B757-200 Freighter; this can be changed using data from the AircraftData worksheet.
Airplane utilization (% 0.9

Freight Trucking

Long Distance Trucking

Study		Emission factor, grams/tonne-km CO	CO_2	HC	NOx	SO_2	PM	
Kürer (Germany)	Longhaul trucks	0.25	140	0.32	3.00	0.18	0.17	
Schoemaker & Bouman (Netherlands)	Trucks & trailers	0.54	109	0.38	1.37	0.10	0.22	
Schoemaker & Bouman (Netherlands)	Truck-tractors & semi trailers	0.34	127	0.34	2.30	0.11	0.19	
OECD (Europe)	Long distance trucks	0.25	140	0.32	3.00	0.18	0.17	
Mean of above studies		0.35	129	0.34	2.42	0.14	0.19	
		Emission factor, grams/kg-mile						**Fuel Consumption**
		CO	CO_2	HC	NOx	SO_2	PM	gal/kg-mile
Mean of above studies, converted to grams/kg-mile [1]		**0.0006**	**0.2076**	**0.0005**	**0.0039**	**0.0002**	**0.0003**	**2.0663E-05**

Local Trucking

Study		Emission factor, grams/tonne-km CO	CO_2	HC	NOx	SO_2	PM	
Kürer (Germany)	Local	1.86	255	1.25	4.10	0.32	0.30	
Schoemaker & Bouman (Netherlands)	Trucks	2.24	451	1.57	5.65	0.43	0.90	
Mean of above studies		2.05	353	1.41	4.88	0.38	0.60	
		Emission factor, grams/kg-mile						**Fuel Consumption**
		CO	CO_2	HC	NOx	SO_2	PM	gal/kg-mile
Mean of above studies, converted to grams/kg-mile [1]		**0.0033**	**0.5681**	**0.0023**	**0.0078**	**0.0006**	**0.0010**	**5.6542E-05**

Other truck data **(NOT USED)**

Study		Emission factor, grams/tonne-km CO	CO_2	HC	NOx	SO_2	PM	VOC
Befahy (Belgium)	Trucks & semi-trailers >10 tonnes	2.10	n/a	0.92	1.85	n/a	0.04	n/a
Whitelegg (Europe)	Road freight overall	2.40	207	0.30	3.60	n/a		1.1

Notes: We use the mean values of these prior studies. Truck characteristics (e.g., category definitions) are not available in these data sourc
Conversion factor: g/tonne-km * 1.609344 km/mile * tonne/1000 kg = g/kg-mile (Conversion factor = 0.001609344)

Source: OECD. 1997. The Environmental Effects of Freight. Table 9. Truck Air Pollution Emission Factors, in grams/tonne-km
Available at http://www1.oecd.org/ech/pub/TRANSP4.PDF

Original sources of studies cited in OECD (1997):

Kürer, R. (1993), Table 5 in "Environment, Global and Local Effects." *In* European Conference of Ministers of Transport, Transport Growth in Question. 12th International Symposium on Theory and Practice in Transport Economics (Paris, 1993)
Kürer cites as the original data source: Umweltbundesamt: "Verkehrsbedingte Luf und Larmbelastungen - Emissionen, Immission

Schoemaker, Theo J. H. and Peter A. Bouman (1991), Tables 14 & 15 in "Facts and Figures on Environmental Effects of Freight Transport in the Netherlands." In Kroon, Martin, Ruthger Smit, and Joop van Ham, eds. (1991), Freight Transport and the Environment. Studies in Environmental Science 45 (Amsterdam: Elsevier, 1991)
The authors cite as the original data source The Netherlands Centraal Bureau voor de Statistiek

Befahy, F. (1993), Table 4 in "Environment, Global and Local Effects" in European Conference of Ministers of Transport, Transport Growth in Question. 12th International Symposium on Theory and Practice in Transport Economics (Paris, 1993)
Befahy cites as the original data source for goods transport: Prognos AG and for passenger transport: Mens en Ruimte Study Gro

OECD (1991), Environmental Policy: How to Apply Economic Instruments. Cited on p. 19 of OECD Environment Directorate (1993), The Social Costs of Transport: Evaluation and Links with Internalisation Policies

Freight Rail

Study	Emission factor, grams/tonne-km CO	CO2	HC	NOx	SO2	PM	VOC	
Kürer	0.15	48	0.07	0.4	0.18	0.07		
Schoemaker & Bouman	0.02	102	0.01	1.01	0.07	0.01		
Whitelegg	0.05	41	0.06	0.2			0.08	
Befahy	0.06		0.02	0.4		0.08		
OECD	0.15	48	0.07	0.4	0.18	0.07		
Mean Value	0.09	59.8	0.05	0.48	0.14	0.06	0.08	
	Emission factor, grams/kg-mile							**Fuel Consumption**
	CO	CO2	HC	NOx	SO2	PM	VOC	gal/kg-mile
Mean Value	**0.0001**	**0.0962**	**0.0001**	**0.0008**	**0.0002**	**0.0001**	**0.0001**	**9.5705E-06**

Notes: We use the mean values of these prior studies,
Conversion factor: g/tonne-km * 1.609344 km/mile * tonne/1000 kg = g/kg-mile (Conversion factor = 0.001609344)

Source: OECD. 1997. The Environmental Effects of Freight. Table 9. Truck Air Pollution Emission Factors, in grams/tonne-km
Available at http://www1.oecd.org/ech/pub/TRANSP4.PDF
For original sources of studies cited in OECD (1997), see Truck Table.

Freight Shipping

Study	Emission factor, grams/tonne-km CO	CO2	HC	NOx	SO2	PM	VOC	
Whitelegg	0.12	30	0.04	0.4			0.1	
Befahy	0.2		0.08	0.58		0.04		
OECD	0.018	40	0.07	0.08	0.5	0.05		
Mean Value	0.11	35.0	0.06	0.35	0.50	0.05	0.10	
	Emission factor, grams/kg-mile							**Fuel Consumption**

General Assumptions	For combustion engines, Reactive Organic Gas (**ROG**) represents evaporative emissions
Freight Trucking & Rail	
Data Sources	OECD. 1997. THE ENVIRONMENTAL EFFECTS OF FREIGHT. Table 9. Truck Air Pollution Emission Factors, in grams/tonne-km http://www1.oecd.org/ech/pub/TRANSP4.PDF

Original sources of studies cited in OECD (1997):

Kürer, R. (1993), Table 5 in "Environment, Global and Local Effects." *In* European Conference of Ministers of Transport,

Transport Growth in Question. 12th International Symposium on Theory and Practice in Transport Economics (Paris, 1993)

Kürer cites as the original data source: Umweltbundesamt: "Verkehrsbedingte Luf und Larmbelastungen - Emissionen, Immissionen, Wirkungen"

UBA-Text 40/91 (Berlin 1991)

Schoemaker, Theo J. H. and Peter A. Bouman (1991), Tables 14 & 15 in "Facts and Figures on Environmental Effects of Freight

Transport in the Netherlands." In Kroon, Martin, Ruthger Smit, and Joop van Ham, eds. (1991), Freight Transport and the

Environment. Studies in Environmental Science 45 (Amsterdam: Elsevier, 1991)

The authors cite as the original data source The Netherlands Centraal Bureau voor de Statistiek

Befahy, F. (1993), Table 4 in "Environment, Global and Local Effects" in European Conference of Ministers of

Transport Growth in Question. 12th International Symposium on Theory and Practice in Transport

Befahy cites as the original data source for goods transport: Prognos AG and for passenger transport: Etude thematique du projet TGV (Brussels, 1989)

OECD (1991), Environmental Policy: How to Apply Economic Instruments. Cited on p. 19 of OECD

The Social Costs of Transport: Evaluation and Links with Internalisation Policies

Calculation: Trucking	Freight truck emissions per kg are calculated as follows: Distance Traveled (miles) * Cargo Shipped (kg) * Emission Factor (g/kg-mile) = grams of emission
Calculation: Rail	Freight railroad emissions per kg **cargo** are calculated as follows: Distance Traveled (miles) * Cargo Shipped (kg) * Emission Factor (g/kg-mile) = grams of emission

D.1.4 Equipment Use Factors

Source: [EPA 1998]

CO_2 emission rate = (BSFC lb/hp-hr)*(453.6 g/lb)*(0.87 g C/ g gas)*(44/12 g CO_2/ g C)
SO_2 emission rate = (BSFC * 453.6 * (1 - 0.022) - HC) * 0.0033 * 2
BSFC = Brake Specific Fuel Consumption
Energy consumption calculated based on diesel heating value of 19,300 Btu/lb
Energy consumption = (BSFC lb/hp-hr)*(19,300 Btu/lb)*(1055.056 J/Btu)/(1x10^6 J/MJ)

Engine Power hp	Model Year	BSFC lb/hp-hr	HC g/hp-hr	CO g/hp-hr	NO_x g/hp-hr	PM g/hp-hr	CO_2 g/hp-hr	SO_x g/hp-hr	Energy Consump. MJ/hp-hr
0 - 11	1990-1995	0.408	1.5	5	10	1	590.37	1.185	8.308
0 - 11	1996	0.408	1.5	5	10	1	590.37	1.185	8.308
0 - 11	1997	0.408	1.5	5	10	1	590.37	1.185	8.308
0 - 11	1998-1999	0.408	1.5	5	10	1	590.37	1.185	8.308
0 - 11	2000	0.408	1.6	5.6	5.9	0.75	590.37	1.184	8.308
0 - 11	2001-2003	0.408	1.6	5.6	5.9	0.75	590.37	1.184	8.308
0 - 11	2004	0.408	1.6	5.6	5.9	0.75	590.37	1.184	8.308
0 - 11	2005	0.408	0.6	5.6	5	0.75	590.37	1.191	8.308
0 - 11	2006-2007	0.408	0.6	5.6	5	0.75	590.37	1.191	8.308
0 - 11	2008+	0.408	0.6	5.6	5	0.75	590.37	1.191	8.308
>11 - 16	1990-1995	0.408	1.5	5	10	1	590.37	1.185	8.308
>11 - 16	1996	0.408	1.5	5	10	1	590.37	1.185	8.308
>11 - 16	1997	0.408	1.5	5	10	1	590.37	1.185	8.308
>11 - 16	1998-1999	0.408	1.5	5	10	1	590.37	1.185	8.308
>11 - 16	2000	0.408	0.7	2	5.2	0.6	590.37	1.190	8.308
>11 - 16	2001-2003	0.408	0.7	2	5.2	0.6	590.37	1.190	8.308
>11 - 16	2004	0.408	0.7	2	5.2	0.6	590.37	1.190	8.308
>11 - 16	2005	0.408	0.6	2	5	0.6	590.37	1.191	8.308
>11 - 16	2006-2007	0.408	0.6	2	5	0.6	590.37	1.191	8.308
>11 - 16	2008+	0.408	0.6	2	5	0.6	590.37	1.191	8.308
>16 - 25	1990-1995	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>16 - 25	1996	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>16 - 25	1997	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>16 - 25	1998-1999	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>16 - 25	2000	0.408	0.7	2	5.2	0.6	590.37	1.190	8.308
>16 - 25	2001-2003	0.408	0.7	2	5.2	0.6	590.37	1.190	8.308
>16 - 25	2004	0.408	0.7	2	5.2	0.6	590.37	1.190	8.308
>16 - 25	2005	0.408	0.6	2	5	0.6	590.37	1.191	8.308
>16 - 25	2006-2007	0.408	0.6	2	5	0.6	590.37	1.191	8.308
>16 - 25	2008+	0.408	0.6	2	5	0.6	590.37	1.191	8.308
>25 - 50	1990-1995	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>25 - 50	1996	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>25 - 50	1997	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>25 - 50	1998-1999	0.408	1.8	5	6.9	0.8	590.37	1.183	8.308
>25 - 50	2000	0.408	0.8	2.5	5.5	0.6	590.37	1.189	8.308
>25 - 50	2001-2003	0.408	0.8	2.5	5.5	0.6	590.37	1.189	8.308
>25 - 50	2004	0.408	0.6	2.5	5	0.6	590.37	1.191	8.308
>25 - 50	2005	0.408	0.6	2.5	5	0.6	590.37	1.191	8.308
>25 - 50	2006-2007	0.408	0.6	2.5	5	0.6	590.37	1.191	8.308
>25 - 50	2008+	0.408	0.6	2.5	5	0.6	590.37	1.191	8.308
>50 - 100	1990-1995	0.408	0.99	3.49	8.3	0.72	590.37	1.188	8.308
>50 - 100	1996	0.408	0.99	3.49	8.3	0.72	590.37	1.188	8.308
>50 - 100	1997	0.408	0.99	3.49	8.3	0.72	590.37	1.188	8.308
>50 - 100	1998-1999	0.408	0.7	1	6.9	0.72	590.37	1.190	8.308
>50 - 100	2000	0.408	0.7	1	6.9	0.72	590.37	1.190	8.308
>50 - 100	2001-2003	0.408	0.7	1	6.9	0.72	590.37	1.190	8.308
>50 - 100	2004	0.408	0.4	1	5.2	0.72	590.37	1.192	8.308
>50 - 100	2005	0.408	0.4	1	5.2	0.72	590.37	1.192	8.308
>50 - 100	2006-2007	0.408	0.4	1	5.2	0.72	590.37	1.192	8.308
>50 - 100	2008+	0.408	0.2	1	3.3	0.72	590.37	1.193	8.308

>100 - 175	1990-1995	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>100 - 175	1996	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>100 - 175	1997	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>100 - 175	1998-1999	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>100 - 175	2000	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>100 - 175	2001-2003	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>100 - 175	2004	0.367	0.4	1	4.5	0.4	531.04	1.072	7.473
>100 - 175	2005	0.367	0.4	1	4.5	0.4	531.04	1.072	7.473
>100 - 175	2006-2007	0.367	0.4	1	4.5	0.4	531.04	1.072	7.473
>100 - 175	2008+	0.367	0.2	1	2.8	0.4	531.04	1.073	7.473
>175 - 300	1990-1995	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>175 - 300	1996	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>175 - 300	1997	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>175 - 300	1998-1999	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>175 - 300	2000	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>175 - 300	2001-2003	0.367	0.4	1	6.9	0.4	531.04	1.072	7.473
>175 - 300	2004	0.367	0.4	1	4.5	0.4	531.04	1.072	7.473
>175 - 300	2005	0.367	0.4	1	4.5	0.4	531.04	1.072	7.473
>175 - 300	2006-2007	0.367	0.2	1	2.8	0.4	531.04	1.073	7.473
>175 - 300	2008+	0.367	0.2	1	2.8	0.4	531.04	1.073	7.473
>300 - 600	1990-1995	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>300 - 600	1996	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>300 - 600	1997	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>300 - 600	1998-1999	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>300 - 600	2000	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>300 - 600	2001-2003	0.367	0.3	1	4.5	0.4	531.04	1.073	7.473
>300 - 600	2004	0.367	0.3	1	4.5	0.4	531.04	1.073	7.473
>300 - 600	2005	0.367	0.3	1	4.5	0.4	531.04	1.073	7.473
>300 - 600	2006-2007	0.367	0.2	1	2.8	0.4	531.04	1.073	7.473
>300 - 600	2008+	0.367	0.2	1	2.8	0.4	531.04	1.073	7.473
>600 - 750	1990-1995	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>600 - 750	1996	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>600 - 750	1997	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>600 - 750	1998-1999	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>600 - 750	2000	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>600 - 750	2001-2003	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>600 - 750	2004	0.367	0.3	1	4.5	0.4	531.04	1.073	7.473
>600 - 750	2005	0.367	0.3	1	4.5	0.4	531.04	1.073	7.473
>600 - 750	2006-2007	0.367	0.2	1	2.8	0.4	531.04	1.073	7.473
>600 - 750	2008+	0.367	0.2	1	2.8	0.4	531.04	1.073	7.473
>750	1990-1995	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>750	1996	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>750	1997	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>750	1998-1999	0.367	0.68	2.7	8.38	0.4	531.04	1.070	7.473
>750	2000	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>750	2001-2003	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>750	2004	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>750	2005	0.367	0.3	1	6.9	0.4	531.04	1.073	7.473
>750	2006-2007	0.367	0.3	1	4.5	0.4	531.04	1.073	7.473
>750	2008+	0.367	0.3	1	4.5	0.4	531.04	1.073	7.473

CARB 1999 Model

Data for Off-Raod Large Compression-Ignited Engines (>25HP) From Offroad Emissions Model.

Source:

equipment	Power hp		1990 po	2010 pop	Use life	Avg Hp (yr)	BSFC (lb/hp-hr)	Activity	Load (hr/yr)
Bore/Drill Rigs	50	P	121	141	3	33	0.54	726	0.75
	120	P	371	433	3	82	0.49	726	0.75
	175	P	86	100	3	150	0.47	726	0.75
	250	N	74	86	3	200	0.47	726	0.75
	500	N	164	191	3	331	0.41	726	0.75
	750	N	79	104	3	654	0.42	726	0.75
	9999	N	132	173	3	987	0.42	726	0.75
Concrete/Industrial Saws	50	P	33	38	16	33	0.54	580	0.73
	120	P	58	67	16	81	0.49	580	0.73
	175	P	2	2	16	175	0.47	580	0.73
Cranes	50	P	34	39	9	43	0.54	1464	0.43
	120	P	429	501	9	93	0.49	1464	0.43
	175	P	785	917	9	149	0.47	1464	0.43
	250	N	720	841	9	208	0.47	1464	0.43
	500	N	268	313	9	334	0.41	1464	0.43
	750	N	55	73	9	562	0.42	1464	0.43
Crawler Tractors	50	P	23	26	16	31	0.54	936	0.64
	120	P	13150	15362	16	82	0.49	936	0.64
	175	P	4450	5198	16	151	0.47	936	0.64
	250	N	3825	4468	16	207	0.47	936	0.64
	500	N	2620	3060	16	323	0.41	936	0.64
	750	N	121	160	16	579	0.42	936	0.64
	9999	N	121	160	16	820	0.42	936	0.64
Crushing/Proc. Equipment	50	P	153	178	16	45	0.54	955	0.78
	120	P	431	503	16	85	0.49	955	0.78
	175	P	182	212	16	171	0.47	955	0.78
	250	N	18	21	16	250	0.47	955	0.78
	500	N	102	119	16	382	0.41	955	0.78
	750	N	4	5	16	602	0.42	955	0.78
	9999	N	4	5	16	1337	0.42	955	0.78
Excavators	50	P	1024	1196	7	35	0.54	1162	0.57
	120	P	2781	3248	7	103	0.49	1162	0.57
	175	P	5365	6267	7	157	0.47	1162	0.57
	250	N	2186	2553	7	222	0.47	1162	0.57
	500	N	1589	1856	7	327	0.41	1162	0.57
	750	N	31	42	7	542	0.42	1162	0.57
Graders	50	P	14	16	10	36	0.54	965	0.61
	120	P	940	1098	10	98	0.49	965	0.61
	175	P	3211	3751	10	162	0.47	965	0.61
	250	N	1992	2327	10	225	0.47	965	0.61
	500	N	56	65	10	300	0.41	965	0.61
	750	N	3	3	10	635	0.42	965	0.61

equipment	Power hp		1990 po	2010 pop	Use life	Avg Hp (yr)	BSFC (lb/hp-hr)	Activity	Load (hr/yr)
Off-Highway Tractors	120	P	1	1	16	115	0.49	855	0.65
	175	P	1168	1364	16	160	0.47	855	0.65
	250	N	1104	1289	16	160	0.47	855	0.65
	750	N	433	571	16	697	0.42	855	0.65
	9999	N	46	60	16	999	0.42	855	0.65
Off-Highway Trucks	175	P	62	72	10	175	0.47	1641	0.57
	250	N	458	535	10	233	0.47	1641	0.57
	500	N	648	757	10	381	0.41	1641	0.57
	750	N	543	714	10	618	0.42	1641	0.57
	9999	N	254	335	10	874	0.42	1641	0.57
Other Construction Equipment	50	P	82	95	16	36	0.54	606	0.62
	120	P	136	158	16	104	0.49	606	0.62
	175	P	187	218	16	137	0.47	606	0.62
	500	N	435	508	16	327	0.41	606	0.62
Pavers	50	P	804	939	8	36	0.54	828	0.62
	120	P	947	1106	8	89	0.49	828	0.62
	175	P	589	688	8	165	0.47	828	0.62
	250	N	71	82	8	250	0.47	828	0.62
	500	N	73	85	8	300	0.41	828	0.62
Paving Equipment	50	P	146	170	16	36	0.54	622	0.53
	120	P	2100	2453	16	82	0.49	622	0.53
	175	P	985	1150	16	152	0.47	622	0.53
	250	N	279	325	16	184	0.47	622	0.53
Rollers	50	P	752	878	8	37	0.54	748	0.56
	120	P	4035	4713	8	84	0.49	748	0.56
	175	P	1622	1894	8	154	0.47	748	0.56
	250	N	230	268	8	218	0.47	748	0.56
	500	N	161	188	8	312	0.41	748	0.56
Rough Terrain Forklifts	50	P	99	115	8	45	0.54	1198	0.6
	120	P	4755	5554	8	83	0.49	1198	0.6
	175	P	609	711	8	166	0.47	1198	0.6
	250	N	34	39	8	227	0.47	1198	0.6
	500	N	22	25	8	341	0.41	1198	0.6
Rubber Tired Dozers	175	P	10	11	16	175	0.47	899	0.59
	250	N	234	273	16	248	0.47	899	0.59
	500	N	360	420	16	358	0.41	899	0.59
	750	N	114	151	16	539	0.42	899	0.59
	9999	N	8	10	16	800	0.42	899	0.59
Rubber Tired Loaders	50	P	257	300	8	46	0.54	1346	0.54
	120	P	6988	8163	8	87	0.49	1346	0.54
	175	P	3938	4600	8	157	0.47	1346	0.54
	250	N	3917	4575	8	220	0.47	1346	0.54
	500	N	1630	1904	8	350	0.41	1346	0.54
	750	N	105	138	8	717	0.42	1346	0.54
	9999	N	11	14	8	877	0.42	1346	0.54
Scrapers	120	P	37	43	12	104	0.49	1090	0.72
	175	P	341	398	12	164	0.47	1090	0.72
	250	N	332	387	12	232	0.47	1090	0.72
	500	N	915	1068	12	356	0.41	1090	0.72
	750	N	135	179	12	615	0.42	1090	0.72
Skid Steer Loaders	50	P	15200	17757	5	37	0.54	811	0.55
	120	P	7964	9303	5	62	0.49	811	0.55

equipment	Power hp		1990 po	2010 pop	Use life	Avg Hp (yr)	BSFC (lb/hp-hr)	Activity	Load (hr/yr)	
Surfacing Equipment	50	P	19	22	16	25	0.54	561	0.45	
	120	P	4	4	16	113	0.49	561	0.45	
	175	P	3	3	16	152	0.47	561	0.45	
	250	N	6	7	16	239	0.47	561	0.45	
	500	N	48	56	16	392	0.41	561	0.45	
	750	N	26	34	16	615	0.42	561	0.45	
Tractors/Loaders/Backhoes	50	P	1839	2148	16	44	0.54	1135	0.55	
	120	P	28552	33355	16	75	0.49	1135	0.55	
	175	P	1885	2202	16	147	0.47	1135	0.55	
	250	N	6	7	16	249	0.47	1135	0.55	
Trenchers	50	P	2672	3121	7	35	0.54	620	0.75	
	120	P	3620	4229	7	69	0.49	620	0.75	
	175	P	396	462	7	153	0.47	620	0.75	
	250	N	35	40	7	237	0.47	620	0.75	
	500	N	45	52	7	331	0.41	620	0.75	
	750	N	3	5	7	624	0.42	620	0.75	
Grand Total				153729	179880	1299	30136	53.28	107622	70.6

D.1.5 Energy Factors

Source [EGRID 2002]

Electricity Emissions

Impacts for NO_x, CO_2, and SO_2 obtained from The Emissions & Generation Resource Integrated Database (E-GRID2002), Version 1.0 files, 2000 data sheets, released December 2002, http://www.epa.gov/airmarkets/egrid/, accessed 8/13/03

Impacts for CO and energy consumption obtained from Monterey County 21st Century General Plan Update Fact Sheet, http://www.co.monterey.ca.us/gpu/FactSheets/energy.htm, accessed 2/10/03 and from US DOE (1994) Evaluation of Electricity Consumption in the Manufacturing Division, http://www.eia.doe.gov/emeu/mecs/mecs94/ei/elec.html, accessed 2/10/03.

3,412 Btu/kWh for site electricity use

CO emission rate(national avg.) = (0.153 lb/MMBtu)*(453.6 g/lb)*(3,412 Btu/kWh)*(1/10^6 MMBtu/Btu)
Energy consumption = (3,412 Btu/kWh)*(1055.056 J/Btu)/(10^6 J/MJ)

Engine Power hp	Model Year	State	HC g/kWh	CO g/kWh	NO_x g/kWh	PM g/kWh	CO_2 g/kWh	SO_2 g/kWh	Energy Consump. MJ/kWh
All	All	AK		0.237	2.21		585.75	0.61	3.60
		AL		0.237	1.38		656.04	3.76	3.60
		AR		0.237	1.10		659.20	1.57	3.60
		AZ		0.237	1.06		533.06	0.74	3.60
		CA		0.237	0.26		287.01	0.08	3.60
		CO		0.237	1.58		913.45	1.85	3.60
		CT		0.237	0.66		335.14	1.03	3.60
		DC		0.237	2.36		1205.19	6.18	3.60
		DE		0.237	1.57		885.20	5.88	3.60
		FL		0.237	1.54		644.30	2.74	3.60
		GA		0.237	1.42		641.33	3.87	3.60
		HI		0.237	2.39		778.67	2.08	3.60
		IA		0.237	1.83		894.49	3.13	3.60
		ID		0.237	0.07		42.20	0.04	3.60
		IL		0.237	1.23		503.24	2.24	3.60
		IN		0.237	2.37		976.58	6.01	3.60
		KS		0.237	1.93		847.57	2.36	3.60
		KY		0.237	2.41		1010.99	5.70	3.60
		LA		0.237	1.15		628.82	1.60	3.60
		MA		0.237	0.95		586.57	2.52	3.60
		MD		0.237	1.59		622.72	4.57	3.60
		ME		0.237	0.66		297.15	0.98	3.60
		MI		0.237	1.53		709.76	3.20	3.60
		MN		0.237	1.77		743.94	2.26	3.60
		MO		0.237	1.96		897.85	2.79	3.60
		MS		0.237	1.55		597.27	3.20	3.60
		MT		0.237	1.29		662.36	0.79	3.60
		NC		0.237	1.33		586.44	3.45	3.60
		ND		0.237	2.27		1085.61	4.41	3.60
		NE		0.237	1.42		701.65	1.95	3.60
		NH		0.237	0.64		321.44	3.12	3.60
		NJ		0.237	0.63		332.29	0.96	3.60
		NM		0.237	2.32		969.35	1.83	3.60
		NV		0.237	1.34		704.05	1.35	3.60
		NY		0.237	0.67		444.38	1.88	3.60
		OH		0.237	2.33		836.44	7.50	3.60
		OK		0.237	1.65		832.76	1.57	3.60
		OR		0.237	0.25		149.36	0.26	3.60
		PA		0.237	1.24		559.79	4.32	3.60
		RI		0.237	0.24		454.37	0.09	3.60
		SC		0.237	0.89		405.18	2.00	3.60
		SD		0.237	1.61		377.72	1.25	3.60
		TN		0.237	1.51		620.76	3.96	3.60
		TX		0.237	1.05		666.11	1.38	3.60
		UT		0.237	2.01		950.50	0.71	3.60
		VA		0.237	1.15		554.81	2.64	3.60
		VT		0.237	0.14		25.83	0.02	3.60
		WA		0.237	0.25		130.40	0.71	3.60
		WI		0.237	1.70		798.63	3.01	3.60
		WV		0.237	2.62		919.60	5.84	3.60
		WY		0.237	1.84		1044.35	1.69	3.60

D.1.6 Environmental Valuation Factors

External Costs (1992$) [Matthews 2000]

Species	External Costs ($/million grams of Air Emissions)			
	Minimum	Median	Mean	Maximum
CO	1	520	520	1,050
NOx	220	1,060	2,800	9,500
SOx	770	1,800	2,000	4,700
PM	950	2,800	4,300	16,200
VOC	160	1,400	1,600	4,400
CO2 eq.	2	14	13	23

External Costs (1997 $)

Years (1997-1992) 5

Discount Rate = 7%

Species	External Costs ($/million grams of Air			
	Minimum	Median	Mean	Maximum
CO	1.40	729.33	729.33	1472.68
NOx	308.56	1486.70	3927.14	13324.24
SOx	1079.96	2524.59	2805.10	6591.99
PM	1332.42	3927.14	6030.97	22721.34
VOC	224.41	1963.57	2244.08	6171.23
CO2 eq.	2.81	19.64	18.23	32.26

D.2 Equipment Descriptions

Sources vary and are listed in the final column of the table.

Type	Brand	hp	Power Source	Fuel Cons[1]	Power (watt)	Emission Code	Source
ON-ROAD VEHICLES							
Pickup Trucks	Custom		gasoline			GR	
Mixer	Volvo WG84	335	diesel	12 mpg		DR	http://equipment.wgint.com/san_roque/concrete_equip.html
	International 5500i	*565*	*diesel*	*10 mpg*		DR	x.asp
(all fuel consump assumed except International)	Italmachine Mariner 55	154.5	diesel	15 mpg		DR	http://www.recpr.com/page.asp?id=28
	Generic 250 hp	250	diesel	13 mpg		DR	R.S. Means Building Construction Cost Data 1999
	Generic 285 hp	285	diesel	13 mpg		DR	R.S. Means Building Construction Cost Data 1999
	Volvo Xpeditor	305 hp	diesel	12 mpg		DR	Construction Equipment June 1999
	Mack Granite	300 hp	diesel	12 mpg		DR	
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Dump Truck	GMC c8500	275 hp	diesel	13 mpg		DR	http://www.gmc.com/commercial/pdfs/cspecs_power.pdf
fuel consumption values are assumed	Sterling L8500	250 hp	diesel	13 mpg		DR	http://www.sterlingtrucks.com/trucks/finalpage.asp?ll=1&mid=1&mo=2&fe=4
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
NON-ROAD VEHICLES							
Air compressor	*Sullair 425*	*124*	*diesel*	*7.00 gal/h*		NR100TO175	http://www.sullair.com/construction/pdf/425.pdf
	Rix 2V1	10	diesel	1.00 gal/h		NR0TO11	
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Concrete pump	Schwing BPL1200	476	diesel	25.00 gal/h		NR300TO600	http://equipment.wgint.com/san_roque/concrete_equip.html#pumptrucks
							http://www.putzmeister.com/products/truckmount/52z_truckspecs.cfm
	Putzmeister 52Z	*300*	*diesel*	*12.00 gal/h*		NR300TO600	http://www.macktrucks.com/product/pdfs/ch0020563.pdf
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA

Type	Brand	hp	Power Source	Fuel Cons[1]	Power (watt)	Emission Code	Source
NON-ROAD VEHICLES							
	Grove RT525E	152	diesel	9.00 gal/h		NR100TO175	http://www.groveworldwide.com/na/eng/crane/
	Grove TMS700E	400	diesel	20.00 gal/h		NR300TO600	http://www.groveworldwide.com/na/eng/crane/
	Terex ATT 600 (60 ton)	313	diesel	12.00 gal/h		NR175TO300	http://www.recpr.com/page.asp?id=16
	Terex ATT 900	160	diesel	7.00 gal/h		NR100TO175	http://www.recpr.com/page.asp?id=17
	Grove TMS 900E	*450*	*diesel*	*25.00 gal/h*		NR300TO600	http://www.groveworldwide.com/na/eng/crane/
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
Crane	none	NA	NA	NA	NA	NA	NA
							http://www.thermadyne.com/prodspot/89_2200.pdf
	Arcair Extreme [arc gouging]		electric	NA	9600	Electric	assume use welder source
Cutting torch	*Thermal Dynamics Pakmaster 150XL*		*electric*	*NA*	*24960*	Electric	http://www.thermadyne.com/prodspot/63_2205.pdf
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
	Gradall 544D	*125*	*diesel*	*8.50 gal/h*		NR100TO175	http://www.constructionequipment.com http://www.gradall.com/gradall/material/models/544dss.pdf
Forklift	Gradall 534D10-45	116	diesel	8.00 gal/h		NR100TO175	http://www.constructionequipment.com http://www.gradall.com/gradall/material/models/534d-10-45ss.pdf
	Terex SS-1056 C	125	diesel	8.50 gal/h		NR100TO175	http://www.recpr.com/page.asp?id=14
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Generator	Caterpillar 3406C TA	519 hp	diesel	26.00 gal/h		NR300TO600	Caterpillar Performance Handbook 1995-1998
	Detroit Diesel 671		diesel	9.60 gal/h			
	Detroit Diesel series 40		diesel	8.70 gal/h			
fuel consumption values in yellow are assumed	Multiquip GA-3.6Hz	8	gasoline	0.55 gal/h		Gasoline	http://www.donhobancompany.com/equipment.htm http://www.all-equipment.com/page0002.html
	Multiquip GA-6HZR	*11*	*gasoline*	*0.65 gal/h*		Gasoline	http://www.donhobancompany.com/equipment.htm http://www.all-equipment.com/page0002.html
	Dewalt DG4300	8	gasoline	0.61 gal/h		Gasoline	http://www.donhobancompany.com/equipment.htm
	Dewalt DG6000	11	gasoline	0.61 gal/h		Gasoline	http://www.donhobancompany.com/equipment.htm
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA

Type	Brand	hp	Power Source	Fuel Cons[1]	Power (watt)	Emission Code	Source
NON-ROAD VEHICLES							
Power saw	Target 14" Quickie		electric	NA	1800	electric	http://www.donhobancompany.com/equipment.htm
	Makita 5740NB		*electric*	NA	*1260*	electric	http://www.mytoolstore.com/makita/
	Circular Saw (small)		electric	NA	1350	electric	http://www.rpc.com/au/products/efn/efnextracts/estima_rating.html
	Circular Saw		electric	NA	1150	electric	http://www.tnpe.com/energyguide.asp http://www.mcecoop.com/acrobat/energyconsumption.pdf
	Circular Saw (7.25")		electric	NA	900	electic	http://www.sunwize.com/aboutpv/images/solar_basics.pdf
	Circular Saw (8.25")		electric	NA	1400	electric	http://www.sunwize.com/aboutpv/images/solar_basics.pdf
	Circular Saw		electric	NA	1100	electric	http://www.powerhousekids.com/_pdf/activity.pdf
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Rebar bender	*Multiquip MB-25*		*electric*	NA	*1200*	Electric	http://www.donhobancompany.com/equipment.htm http://all-equipment.com/page0002.html
	Diamond DBD-32X		electric	NA		Electric	http://www.all-equipment.com/page0002.html
	Diamond DBD-25X		electric	NA		Electric	http://www.all-equipment.com/page0002.html
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Rebar cutter	Benner-Nawman DC-20WH		electric	NA	1200	Electric	http://www.donhobancompany.com/equipment.htm
	Diamond DC-32X		electric	NA		Electric	http://www.all-equipment.com/page0002.html
	Diamond DC-25X		electric	NA		Electric	http://www.all-equipment.com/page0002.html
	Diamond DC-20X		electric	NA	1200	Electric	http://www.all-equipment.com/page0002.html
	Multiquip HBC-19		electric	NA	1080	Electric	http://www.southern-tool.com/store/multiquip_rebar_cutters.html
	Multiquip HBC-25		electric	NA	1440	Electric	http://www.southern-tool.com/store/multiquip_rebar_cutters.html
	Multiquip BC-25		*electric*	NA	*1200*	Electric	http://www.southern-tool.com/store/multiquip_rebar_cutters.html
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Concrete Vibrator	Oztec 1.2oz		electric	NA	1080	Electric	http://www.donhobancompany.com/equipment.htm http://www.southern-tool.com/store/media/VibChart.pdf
	Oztec 1.8 oz		electric	NA	1800	Electric	http://www.donhobancompany.com/equipment.htm http://www.southern-tool.com/store/media/VibChart.pdf

Type	Brand	hp	Power Source	Fuel Cons[1]	Power (watt)	Emission Code	Source
NON-ROAD VEHICLES							
Concrete vibrator (cont) [yellow fuel consumption are assumed]	Oztec 2.4 oz		electric	NA	2040	Electric	http://www.donhobancompany.com/equipment.htm http://www.southern-tool.com/store/media/VibChart.pdf
	Oztec 3.2 oz		electric	NA	2280	Electric	http://www.donhobancompany.com/equipment.htm http://www.southern-tool.com/store/media/VibChart.pdf
	Generic	2	electric	NA	1491.38	Electric	R.S. Means Building Construction Cost Data 1999
	Generic	3	electric	NA	2237.07	Electric	R.S. Means Building Construction Cost Data 1999
	Oztec GV-5	5	gasoline	0.40 gal/h		gasoline	http://www.southern-tool.com/store/media/VibChart.pdf
	Oztec GV-5H	*5.5*	*gasoline*	*0.40 gal/h*		gasoline	http://www.southern-tool.com/store/media/VibChart.pdf
	Generic	5	gasoline	0.40 gal/h		gasoline	R.S. Means Building Construction Cost Data 1999
	Generic	8	gasoline	0.60 gal/h		gasoline	R.S. Means Building Construction Cost Data 1999
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Welder	*Miller Heavy Duty Gold Star 302*		*electric*	NA	*9600*	Electric	http://www.weldingmart.com/
	Maxstar 300DX		electric	NA	7500	Electric	http://www.weldingmart.com/
	Invision 456MP		electric	NA	17100	Electric	http://www.weldingmart.com/
	Invision 354MP		*electric*	NA	*9600*	Electric	http://www.weldingmart.com/
	Welder 140A		electric	NA	4000	Electric	http://www.rpc.com/au/products/efn/efnextracts/estima_rating.html
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Dozer with ripper	Caterpillar D8N	285 hp	diesel	18.87 gal/h		NR175TO300	Caterpillar Performance Handbook 1995-1997
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Excavator	John Deere 200C	141 hp	diesel	9.73 gal/h		NR100TO175	http://www.deere.com/en_US/cfd/construction/deere_const/excavators/200clc_general.html?sidenavstate=11
	Caterpillar 375	428 hp	diesel	24.72 gal/h		NR300TO600	http://cmms.cat.com/cmms/servlet/cat.dcs.cmms.servlet.GetFamilyFull?classid=406&langid=en&rgnid=NACD&view=html&familyid=464&dsfFlag=0
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Asphalt Paver	Blaw-knox PF-5510	184 hp	diesel	12.18 gal/h		NR175TO300	http://www.road-development.irco.com/index_read.html
	Cedarapids CR451	172 hp	diesel	11.39 gal/h		NR100TO175	
	Dynapac F25C	126 hp	diesel	8.34 gal/h		NR100TO175	
	Dynapac F30C	196 hp	diesel	12.97 gal/h		NR175TO300	
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA

Type	Brand	hp	Power Source	Fuel Cons[1]	Power (watt)	Emission Code	Source
NON-ROAD VEHICLES							
Tandem Roller	Ingersol rand DD130	174 hp	diesel	11.52 gal/h		NR100TO175	http://www.road-development.irco.com/index_read.html
	Ingersol rand DD110	125 hp	diesel	8.63 gal/h		NR100TO175	http://www.road-development.irco.com/index_read.html
	Ingersol rand DD90	110 hp	diesel	7.28 gal/h		NR100TO175	http://www.road-development.irco.com/index_read.html
	Ingersol rand DD90HF	110 hp	diesel	7.28 gal/h		NR100TO175	
	Hypac C778B	125 hp	diesel	8.27 gal/h		NR100TO175	http://www.hypac.com/equip/index.htm
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Vibratory Soil Compactor	Dynapac CA 262D	150 hp	diesel	9.93 gal/h		NR100TO175	
	Ingersoll-Rand SD100D	125 hp	diesel	32.65 gal/h		NR100TO175	http://www.road-development.irco.com/downloads/SD100.pdf
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Tanker	Sterling LT7500	250 hp	diesel	0.08 gal/h		DR	
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Texture Concrete Curing Machine	Gomaco T/C 400	70 hp	diesel	5.32 gal/h		NR50TO100	
	Wirtgen TCM 850	47 hp	diesel	2.27 gal/h		NR25TO50	http://www.wirtgen.de/w/eng/eprod/etcm0850.html
	Wirtgen TCM 1600	49 hp	diesel	2.27 gal/h		NR25TO50	http://www.wirtgen.de/w/eng/eprod/esp.html
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Wheel Loader	John Deere 644E	160 hp	diesel	10.59 gal/h		NR100TO175	http://www.deere.com/deerecom/Contractors/New+Equipment/default.htm?menu=2
	John Deere 624E	135 hp	diesel	9.32 gal/h		NR100TO175	http://www.deere.com/deerecom/Contractors/New+Equipment/default.htm?menu=3
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Pedestal Boom System & Breaker	Rammer C 350	40 hp	diesel	3.04 gal/h		NR25TO50	http://www.rammer.com/news/rammermag/booms.html
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Pneumatic Roller	Dynapac CP132	100 hp	diesel	6.90 gal/h		NR100TO175	http://www.dynapac.com/index_main.asp
	Dynapac CP221	100 hp	diesel	6.62 gal/h		NR100TO175	http://www.dynapac.com/index_main.asp
	Dynapac CP134	100 hp	diesel	6.62 gal/h		NR100TO175	http://www.dynapac.com/index_main.asp
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA

Type	Brand	hp	Power Source	Fuel Cons[1]	Power (watt)	Emission Code	Source
NON-ROAD VEHICLES							
Motor Grader	Caterpillar 120H	125 hp	diesel	8.30 gal/h		NR100TO175	
	Caterpillar 140H NA	165 hp	diesel	10.92 gal/h		NR100TO175	
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Backhoe Loader	Caterpillar 420D	88 hp	diesel	6.69 gal/h		NR50TO100	http://cmms.cat.com/cmms/servlet/cat.dcs.cmms.servlet.GetFamilyFull?classid=406&langid=en&rgnid=NACD&view=html&familyid=456&dsfFlag=0
	John Deere 710G	118 hp	diesel	8.14 gal/h		NR100TO175	http://www.deere.com/en_US/cfd/construction/deere_const/media/pdf/DKA410_710G0301.pdf
	Custom	Edit	Edit	Edit	Edit	Edit	Edit
	none	NA	NA	NA	NA	NA	NA
Custom Equipment	Transport Custom	Edit	Edit	Edit	Edit	Edit	EDIT
	Plate Compactor IngRand BXR60	3.5	gasoline	0.30 gal/h	NA	gasoline	http://www.road-development.irco.com/index_read.html

NOTES:

(1) Fuel consumption values shown in shaded cells are estimated based on similar equipment.

D.3 Cost Information

COST SUMMARIES

TEXT CODES

Bold values are from Means 1997 or other listed source.

Normal text values are interpolated between known values.

Italicized values for Cost B are calculated as follows, where the cost for A is known:

CostB=CostA*(DiameterA/DiameterB)^0.6 [Peters 2003]

PIPE and FITTINGS COST and DIMENSIONS

Source: costs from Means 1997 [1997 $], dimensions from Nayyar 2002 and Mays 2000

	AC[g]		Concrete		Ductile Iron		PVC		Steel			Mortar lining (in)			
Diameter (in.)	1997$	Wall thickness (in)	1997$	Wall thickness (in)	1997$	thickness (in)	1997$	Wall thickness	1997$	Wall thickness (in)	DI 90 degree bend (1997$)	DI	Steel	Concrete	Fitting Weight (lb)
1	*$ 1*	*0.75*	NA		NA	NA	*$ 1*	0.18	**$ 2**	0.18	*$ 46*	0.0625	0.313	NA	*10*
2	*$ 2*	*0.75*	NA		**$ 4**	*0.25*	**$ 1**	0.22	**$ 3**	0.22	*$ 69*	0.0625	0.313	NA	*25*
4	*$ 3*	*1*	NA		**$ 7**	0.25	**$ 3**	0.34	**$ 8**	0.34	**$ 105**	0.0625	0.25	NA	50
6	**$ 4**	*1.25*	NA		**$ 8**	0.25	**$ 5**	0.43	**$ 17**	0.43	**$ 159**	0.0625	0.25	NA	80
8	**$ 4**	*1.5*	NA		**$ 10**	0.25	**$ 8**	0.50	**$ 7**	0.50	**$ 239**	0.0625	0.25	NA	140
10	**$ 4**	*2*	NA		**$ 13**	0.26	**$ 9**	0.59	**$ 9**	0.50	**$ 254**	0.0625	0.25	0.5	215
12	**$ 6**	*2*	**$ 25**	2	**$ 17**	0.28	**$ 10**	0.69	**$ 10**	0.50	**$ 403**	0.0938	0.25	0.5	325
14	$ 6	*2*	$ 29	2	**$ 20**	0.31	**$ 15**	0.75	**$ 24**	0.50	**$ 541**	0.0938	0.313	0.5	385
16	$ 7	*2.125*	$ 34	2.125	**$ 2**	0.34	**$ 19**	0.84	$ 25	0.50	**$ 615**	0.0938	0.313	0.5	505
18	**$ 8**	*2.25*	$ 39	2.25	**$ 23**	0.36	**$ 25**	0.94	$ 26	0.50	**$ 915**	0.0938	0.313	0.75	630
20	$ 9	*2.375*	$ 43	2.375	**$ 28**	0.38	**$ 31**	1.03	$ 28	0.50	**$ 1,057**	0.0938	0.313	0.75	810
24	**$ 12**	*2.5*	**$ 53**	2.5	**$ 41**	0.43	**$ 44**	*1.22*	**$ 31**	0.50	**$ 1,598**	0.0938	0.375	0.75	1240
30	*$ 14*	*2*	$ 60	2	*$ 47*	0.49	**$ 59**	*1.67*	**$ 42**	0.50	*$ 1,827*	0.125	0.375	0.75	2105
36	*$ 15*	*2.75*	**$ 67**	2.75	*$ 53*	0.56	**$ 72**	*2.00*	**$ 47**	0.63	*$ 2,039*	0.125	0.375	0.75	3285
48	NA		**$ 99**	4	*$ 63*	0.7	NA		**$ 99**	0.63	*$ 2,423*	0.125	0.5	0.75	6790
60	NA		**$ 151**	5	NA		NA		**$ 155**	0.63	*$ 2,770*	0.125	0.5	0.75	*10500*
72	NA		*$168*	6	NA		NA		**$ 187**	0.63	*$ 3,090*	0.125	0.5	0.75	*14000*

g assumed based on non-reinforced pipe cost; AC pipe is no longer for sale.

a PE values used to estimate pipe >24 in

VALVE COSTS

	Cast iron				
(in)	butter fly	check	gate	globe	Weight (lb)[c]
1	NA	*107*	*103*	*146*	*10*
2	NA	*162*	*156*	*221*	*25*
4	NA	**245**	**237**	**335**	*50*
6	NA	**415**	**288**	**585**	*80*
8	NA	**845**	**420**	**1075**	*140*
10	NA	1460	617.5	1938	*215*
12	NA	**2075**	**815**	**2800**	*325*
14	**1500**	3313	NA	3600	*385*
16	2000	**4550**	NA	**4400**	*505*
18	**2500**	**6750**	NA	5825	*630*
20	**3150**	9025	NA	**7250**	*810*
24	**4400**	**11300**	NA	**8600**	*1240*
30	*5030*	*12919*	NA	*9832*	*2105*
36	*5612*	*14412*	NA	*10969*	*3285*
48	*6669*	*17128*	NA	*13035*	*6790*
60	*7625*	*19581*	NA	*14903*	*10500*
72	*8506*	*21845*	NA	*16625*	*14000*

c assumed to equal fitting weight

COST SUMMARIES

TANK COSTS [MEANS 1997]

Tank Capacity (MG)	0.001	0.005	0.02	0.045	0.05	0.1	0.25	0.5	0.75	1	2	4	5	6	8	10
Redwood			14,300	25,000	28,500	63,500	168,500	343,500	518,500	693,500	1,393,500	2,793,500	3,493,500	4,193,500	5,593,500	6,993,500
Steel																
Total Cost						96,000	116,000	195,000	230,000	310,000	560,000	890,000	1,045,000	1,200,000	16,000,000	2,200,000
Material Cost	*3,477*	*8,703*				48,000	58,000	97,500	115,000	155,000	280,000	445,000	522,500	600,000	8,000,000	1,100,000

Materials %[d] 50%

d [Peters 2003]

PRE-CAST VALVE BOX COST [MEANS 1997]

SA (ft)	16	16	36	36	50	60	70	70	78
Min SA (ft)	0	0	16	16	36	50	60	60	70
Depth (ft)	4	6	4	6	5	6	5	6	6
Volume (cf)	64	96	144	216	250	360	350	420	468
Precast Concrete	1100	1550	1500	1550	1850	1925	2050	2275	3000
$/cf	17.19	16.15	10.42	7.18	7.40	5.35	5.86	5.42	6.41
	16.67		7.29		5.60		5.91		

Assumed valve box costs up to 500 cf. ($/cf)		
0-50	0	19.67
50-100	50	16.40
100-200	100	10.25
200-300	200	7.17
300-400	300	5.51
400-400	400	5.81
Over 500 cf constructed as cast in place		

COST SUMMARIES

WELL COSTS

Diameter (in.)	Stainless Steel	PVC	gravel pack
	($/lf)		
2	$ 34	$ 1	
4	$ 48	$ 2	
6	$ 76	$ 3	$ 0
8	$ 99	$ 5	$ 0
16	$ 183		$ 2

PUMP COSTS

Source: Means 1997; weights from www.goulds.com

SMALL HORSEPOWER

Motor Capacity (hp)	Bronze, flange connection	Cast iron	High head, bronze impellor	Average price	Wt (lb)
0.25	$ 520	$ 520		$ 520	31
0.33	$ 700	$ 700		$ 700	31
0.5	$ 1,225	$ 730	$ 640	$ 865	31
0.75	$ 1,325	$ 840	$ 685	$ 950	46
1	$ 2,150	$1,200	$ 825	$ 1,392	50
1.5			$ 1,000	$ 1,000	50

LARGE HORSEPOWER

Motor Capacity (hp)	Bronze impellor	Base mounted bronze impeller	End suction	Double suction	Centrifugal on base	Horizontal split case single stage	Horizontal split case, dual stage	Vertical submerged		Wt
3			$ 3,650					$5,275	$ 4,463	67
5	$ 1,325	$1,750			$1,725				$ 1,600	100
7.5	$ 1,850	$2,050				$ 2,875			$ 2,258	140
10	$ 2,275	$2,150	$ 3,925	$ 5,050	$2,050			$5,525	$ 3,496	*170*
15	$ 2,725	$2,975	$ 4,275	$ 5,200	$2,225	$ 3,775		$5,675	$ 3,836	*200*
20	$ 3,025	$3,250	$ 4,550		$3,225	$ 4,550			$ 3,720	*200*
25	$ 3,600	$3,425				$ 4,700		$5,800	$ 4,381	*225*
30			$ 4,925	$ 7,050	$3,425			$6,500	$ 5,475	*225*
40					$3,675	$ 6,125	$ 4,025		$ 4,608	*250*
50				$ 7,575		$ 7,700	$ 4,475		$ 6,583	*250*
60				$ 8,475	$5,300				$ 6,888	*275*
75				$ 10,300	$7,000	$ 10,400	$ 4,750		$ 8,113	*275*
100				$ 12,900	$8,750	$ 11,500	$ 5,050		$ 9,550	*300*
150				$ 15,700		$ 14,200			$14,950	*350*
200						$ 15,700	$ 13,400		$14,550	*400*
1000						$ 27,136	$ 23,161		$25,149	*900*

Larger Pump Sizes estimated using Peters 2003

COST SUMMARIES

FLOWMETERS COSTS
SOURCE: MEANS 1997.

Diameter (in.)	Water orifice insert type	Pitot tube weld-on mounting	Pitot tube weld on wet tap with probe	Pitot tube clamp on	Average
6	$ 207	$ 269	$ 385	$ 510	$ 343
8	$ 294	$ 385	$ 400	$ 560	$ 410
10	$ 340	$ 415	$ 430	$ 585	$ 443
12	$ 565	$ 445	$ 465	$ 655	$ 533
14		$ 510	$ 530	$ 885	$ 642
16		$ 600	$ 630	$ 1,025	$ 752
18		$ 640	$ 675	$ 1,100	$ 805
20		$ 695	$ 725	$ 1,200	$ 873
24		$ 775	$ 810	$ 1,300	$ 962
30		*$ 886*	*$ 926*	*$ 1,486*	$1,099
36		*$ 988*	*$ 1,033*	*$ 1,658*	$1,227

CHEMICAL COSTS
Source: OWD 2003 unless otherwise noted

Chemical	Sector	$/lb	$/gal	SOURCE
Alum	Industrial chemicals	$ 0.06		OWD
Aqueous ammonia	Industrial chemicals	$ 0.06		OWD
Calcium carbonate	Lime	$ 0.06		CMR
Caustic Soda	Industrial chemicals	$ 0.04	$ 0.59	OWD
Chlorine	Industrial chemicals	$ 0.14		OWD
Ferric chloride	Industrial chemicals	$ 0.12		CMR
Fluorosilicic acid	Industrial chemicals	$ 0.09		CMR
Hydrochloric acid	Industrial chemicals	$ 0.05		OWD
Polyelectrolyte	Chems and preps	$ 0.45		Assumed equal to polymer
Polymer	Polymers	$ 0.45		OWD
Scale inhibitor (King Lee)	Chems and preps	$ 0.92		OWD
Sodium hypochlorite	Industrial chemicals	$ 0.06	$ 0.68	OWD
Sulfuric acid	Industrial chemicals	$ 0.06		OWD
Zinc orthophosphate	Industrial chemicals	$ 0.35		CMR f

f assumed equal to phosphoric acid and Zn sulfate (together 80% of Zn orthophosphate)

FILTER MEDIA COSTS
Source: gravel - Means 1997; anthracite, sand -
http://www.ce.memphis.edu/1112/projects/filter/Spring%202003/filter_description_s03.htm

Sand	$ 27	per cf
Gravel	$ 22	per cy
Anthracite	$ 25	per cf

CARTRIDGE FILTER COSTS
Source: Tampa article

	Total Cost	Steel Casing	Membrane
2002$	$10	$2.50	$7.50
1997$	$8.97	$2.24	$6.73

D.4 General Construction Parameters

CONSTRUCTION PARAMETERS
Source: assumed, unless otherwise noted

Compaction lift height (ft)	0.5	
Recompaction %	0.8	
Wall thickness (ft)	1	[Means 1997]
Forms reuse (number of times)	3	
Fdtn overexcavation depth (ft)	1	
Fdtn overexcavation width (ft)	4	

TRANSPORT DISTANCES
Source: assumed, unless otherwise noted

Offhaul Distance, round trip (mi)	30
Avg. Onsite haul distance (ft)	300
Concrete delivery, round trip (mi)	40
Landfill distance, round trip (mi)	60

UNIT WEIGHTS (lb/cf)
Source: assumed, unless otherwise noted

Plastic	75	Nayyar 2002; average of PVC and PE
Concrete	130	
Cast iron	446	Nayyar 2002
Steel	484	Nayyar 2002
Mortar	90	
Wood	40	
Sand	110	Caterpillar 1996
Gravel	120	Caterpillar 1996
Sludge	85	
Anthracite	70	Caterpillar 1996

CHEMICAL DENSITIES (lb/gal)

Caustic soda	12.7	ASCE 1998
Sodium hypochlorite	9.7	www.syndel.com/msds/sodium_hypochlorite_msds.html

UNIT COSTS
Source: Means 1997, unless otherwise noted

		Unit	Cost
Cement mortar		cy	$ 2.85
Redwood		lf	$ 1.39
Steel			
Reinforced Concrete			
	Ready-mixed	cy	$ 59.02
	Rebar	cy	$ 2,923.44
Plywood (for 3 uses)		sf	$ 0.98
Wood (12 x 2)		lf	$ 1.39
Gravel		cy	$ 8.65

AUXILLARY EQUIPMENT- assumed percentage of equipment costs
Source: Peters 2003, Table 6-9 and 6-16, for fluid processing plant
Labor is 50% of cost and cost is 50% lower than average for simple processing plant

	Installed Cos	Material Cost
Electrical	11%	2.8%
Instrumentation and Contro	36%	9.0%
Piping	68%	17.0%
Yard improvements	10%	2.5%
Buildings	18%	4.5%
Service facilities	70%	18%

Composition of Reinforced Concrete (by volume)
Source: Assumed

Concrete	98%
Reinforcing steel	2%

D.5 Equipment Use Parameters

Equipment Data

Source: Means 1997

Interpolated or estimated values are in yellow.

All excavation assumed to be in common earth.

Trench excavation

Bucket Width ft	Bucket Capacity cy	Excavator	Hourly Output (cy)
1.5	1	JD 200C	50
2.25	1.5	JD 200C	67.5
3.75	2.5	JD 200C	125
5.25	3.5	Cat 375	210
6	4	Cat 375	225
6.691666667	4.75	Cat 375	281.25

Pipe Data

Pipe Diameter
1
2
4
6
8
10
12
14
16
18
20
24
30
36
48
60
72

Pipe Material	Codes		lb/cf
Asbestos cement	2	3	90
Concrete, mortar-lined	4	5	130
Concrete cylinder	4	5	130
Ductile Iron	6	7	446
Ductile Iron, Mortar-lined	6	7	446
PVC	8	9	75
Steel	10	11	484
Steel, Mortar-lined	10	11	484

Other Excavation

CY	Model	Hourly Output (cy)
0	JD 200C	50
250	JD 200C	67.5
500	JD 200C	125
1500	Cat 375	210
5000	Cat 375	225
10000	Cat 375	281.25

Loader

Estimated using 50% theoretical values

Model	Bucket Cap (cy)	Hourly Output (cy)
JD644E	4	160

Equipment Data

Source: Means 1997

Interpolated or estimated values are in yellow.

Loader

Estimated using 50% theoretical values

Model	Bucket Cap (cy)	Hourly Output (cy)
JD644E	4	160

Compaction

For trenching

Vibratory Plate Compactor

Source: Means; assumes 3 passes

Lift height (ft)		0.5	0.67	1
Plate width	Model	Hourly Output (CY)		
1.5	Plate	538	*1385*	2232
	Dynapac CA 262D			
6.888	Ingersoll-Rand SD100D	550	494	438

Crane

For large-diameter pipe, operates same hours as excavator

For well pump installation, one day per pump.

For tank and large equipment installation, hrs per use: 2.5

Concrete pump

Assume pump is necesssary for half of concrete placement; so hourly output is doubled.

Hourly Output (CY) 40

Concrete vibrator

Hourly Output (CY) 26.67 [assumed based on 10 sec per 2 cubic feet]

Rebar

Assumes one cut and one bend per 8 ft of 1"D rebar.

	Cutter	Bender
Time per cut/bend (min)	0.2	0.3
Vol of reference rebar (cf)	0.043633231	
Hourly output (cy)	0.484813681	0.323209

Concrete Truck

Capacity (cy) 15

Dump Truck

Capacity (cy) 12

Drill Rig Output (lf/hr)

Diameter (in)	Output
2	34.125
14	6.7875
16	6.0375

D.6 References

[ATA 2001]. *Annual Report 2001*. Air Transport Association, http://www.airlines.org/econ/files/2001AnnualReport.pdf (Accessed April 27, 2004.)

[CARB 2002]. "Off-Road Emissions Model; Mailout MSC #99-32." California Air Resources Board. http://www.arb.ca.gov/msei/msei.html. Accessed May 1, 2002.

[CMU 2004]. "Economic Input-Output Life-cycle Assessment (EIO-LCA)." home page. Carnegie Mellon University Green Design Initiative. http://www.eiolca.net. (Accessed March 23, 2004.)

[E-GRID 2002]. *The Emissions and Generation Resource Integrated Database (E-GRID2002) Version 1.0, 2000 Data*. U.S. Environmental Protection Agency: Washington, D.C., 2002.

[EEA 2002]. *EMEP/CORINAIR Emission Inventory Guidebook - 3rd edition*. 2002, European Environmental Agency. http://reports.eea.eu.int/EMEPCORINAIR3/en (Accessed April 27, 2004.)

[ENR 2004]. "Construction Cost Index" home page. Engineering News Record. http://www.enr.com/features/conEco/costIndexes/default.asp (Accessed January 2004).

[EPA 1995]. "Compilation of Air Pollutant Emission Factors AP-42, Mobile Sources, Heavy-Duty Diesel Trucks," United States Environmental Protection Agency: Washington, D.C., June 1995. http://www.epa.gov/otaq/models/ap42/ap42-h7.pdf. (Accessed April 23, 2002.)

[EPA 1998]. Beardsley, M. and C. Lindhjem. Exhaust Emission Factors for Non-Road Emission Modeling- Compression Ignition. Environmental Protection Agency: Washington, D.C., 1998.

[IPCC 1999]. *Aviation and the Global Environment: Aviation Fuels*. Intergovernmental Panel on Climate Change. http://www.grida.no/climate/ipcc/aviation/109.htm (Accessed April 27, 2004.)

[Matthews 2000]. Matthews, H. S. and L. B. Lave. "Applications of Environmental Valuation for Determining Externality Costs." *Environmental Science & Technology* 34(8): 1390-1395, 2000.

[Means 1997]. Page, J., ed. *Heavy Construction Cost Data*, 12th ed. R.S. Means Corporation: Kingston, MA, 1997.

[Nayyar 2002]. Nayyar, M.L., *Piping Databook*. McGraw-Hill: New York, 2002.

[OECD 1997]. *The Environmental Effects of Freight*. Organization for Economic Cooperation and Development: Paris, France, 1997.

[OWD 2003]. Site visit to Oceanside Water Utilities Department, Oceanside, California. August 6-8, 2003.

[Peters 2003]. Peters, M.S.; Timmerhaus, K.D.; West, R. *Plant Design and Economics for Chemical Engineers*. 5th ed. McGraw-Hill: New York, 2003.

[Romano 1999]. Romano, D., D. Gaudioso, and R. De Lauretis, "Aircraft Emissions: A Comparison of Methodologies Based on Different Data Availability." *Environmental Monitoring and Assessment*, 56: 51-74, 1999.

[Sorenson 1995]. Sorenson, L. and N. Kilde, *Waste Treatment and Disposal: Air Traffic*. 1995, Risoe National Laboratory, Systems Analysis Department; European Environmental Agency. http://eionet.eea.eu.int/aegb/cap08/b851.htm (Accessed January 22, 2002).

[Stokes 2004]. Stokes, J. "Life-cycle Assessment of Alternative Water Supply Systems in California." Ph.D. Dissertation. University of California, Berkeley, 2004