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FINAL PROJECT REPORT

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

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PREFACE

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

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Life-Cycle Energy Assessment of Alternative Water Supply Systems in California is the final report for the Life-Cycle Energy Assessment of Alternative Water Supply Systems in California – Extensions and Refinements project (Contract Number 500-02-004, Work Authorization MR-048) conducted by the University of California, Berkeley. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

Providing water and wastewater services in California is often energy-intensive. The need for alternative water sources (for example, from desalination) and tougher regulations on wastewater utilities lead to higher energy and resource requirements. The environmental implications of these services should be incorporated into design and planning decisions to develop a more environmentally responsible water and wastewater system.

Life-cycle assessment is a quantitative, comprehensive method used in this research to account for energy consumption and environmental emissions caused by extracting raw materials, manufacturing, transporting, constructing, operating, maintaining, and decommissioning infrastructure and to incorporate these implications in decision-making. In this research, life-cycle assessment was used to evaluate water and wastewater systems in California by 1) creating and revising pubically available decision-support softwares, the Water-Energy Sustainability Tool and Wastewater-Energy Sustainability Tool, useful to utilities and other industry professionals to evaluate their design and planning alternatives, and 2) evaluating case studies to determine the factors and parameters that affect the systems' energy use and environmental effects. Results were reported for the life-cycle phases, system functions, and activities. The tools created are available for public release.

The study results showed and quantified that:

- Including the life-cycle effects of electricity generation, rather than just direct (for example, smokestack) emissions can make a significant difference in the outcomes.
- Desalination, particularly of seawater, is the most environmentally burdensome water supply alternative.
- Certain conservation programs have lower life-cycle energy use compared to available water supply.
- Wastewater systems can significantly reduce their greenhouse gas emissions by recovering methane from their treatment process to generate electricity.
- Both water and wastewater systems exhibit economies of scale in their treatment processes.
- Results for both water and wastewater systems are site-specific.

Keywords: Life-cycle assessment, water supply, wastewater, energy end-use, desalination, recycled water

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EXECUTIVE SUMMARY

Introduction

Water and energy are interconnected. Prior research has shown that the energy required for water processing contributes significantly to water's environmental effects. Worldwide, pumping and treating urban water and wastewater consume as much as three percent of energy, which will only increase as population and demand for better treatment and sanitation increase. In California, water-related services use significant portions of the state's electricity and natural gas. Energy use will grow as desalination or other energy-intensive sources are adopted in water-scarce areas. Growth in desalination will come at considerable energy and environmental costs.

The environmental impacts of wastewater are also of concern. Changes in regulations on wastewater discharge requirements may increase the associated energy use. Wastewater treatment plants are regulated to limit their impact on the environment; however, regulations focus on chemical concentrations in liquid outflow and solid waste. They rarely consider the broader effects associated with the wastewater system's life cycle, including material production and use, infrastructure construction and maintenance, and energy production impacts. But the regulatory landscape is changing; for example, recent California legislation, the Global Warming Solutions Act of 2006 (Núñez, Chapter 488, Statutes of 2006), regulates greenhouse gas emissions associated with wastewater treatment plants.

While rarely considered, the environmental effects of material and energy intensity should complement conventional design criteria when making water utility decisions. Infrastructure construction and maintenance as well as material production and delivery contribute to energy use and the overall impacts, or "environmental burden." The energy and materials used and the construction processes needed to install this infrastructure also increase a utility's life-cycle environmental effects. Desalination plants, for example, are being considered by some coastal California utilities to provide a reliable and local water source. Adding solar power capacity is assumed to reduce greenhouse gas emissions, without considering the emissions created during the manufacturing, installation, operation, and decommissioning of solar photovoltaic or concentrated solar power plants.

The tool described in this report uses a life-cycle assessment framework that allows a utility to compare the resulting greenhouse gas emissions in their decision process more comprehensively. Life-cycle assessments evaluate the environmental effects associated with all stages, from original material extraction, material processing, manufacturing, distribution, use, maintenance, and disposal. The life-cycle assessment framework presented in this report can also evaluate many other systemwide or process-specific decisions, such as selecting pipe materials, filters (conventional vs. membrane), disinfection processes, or different operational strategies.

Water and wastewater services are necessary for healthy life and will be provided even when the best available alternative is costly, but system planners should strive to select options that minimize energy and material use and the associated environmental effects from the use of these resources.

Purpose

The research described in this report is an enhancement and expansion of an earlier method to analyze the energy and environmental effects associated with water supply infrastructure. This earlier study, by the same authors of this report, is titled *Life-cycle Energy Assessment of Alternative Water Supply Systems in California* and is available on the Energy Commission website at http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-101.html. The original project was a broad-scope, screening-level analysis of water supply infrastructure that developed and used the Water Energy Sustainability Tool. The initial study sought to identify the most important parameters for such assessments and to provide focus for more detailed analyses. Therefore, the research described herein is intended to refine and expand the original work by making it more comprehensive, precise, and robust, as well as adding case studies to demonstrate the utility of such an approach.

This research provides additional information that can be used by water and wastewater utilities and other industry professionals to improve design, planning and operational decisions for these public services. Two Microsoft Excel®-based decision support tools, the revised Water-Energy Sustainability Tool and the new Wastewater-Energy Sustainability Tool, are provided to allow users to calculate the life-cycle energy and environmental implications of infrastructure associated with California's water and wastewater systems.

Objectives

The objectives of this project are to:

- Revise the Water Energy Sustainability Tool to assess alternative energy sources and custom energy mixes, including options for renewable energy from solar, wind, and biomass sources.
- Update the Water Energy Sustainability Tool to analyze other scenarios (for example, groundwater, surface water, or alternative treatment processes) or alternative scenarios (such as using chlorine versus ultraviolet disinfection).
- Create a simplified tool that will calculate emission factors for common materials in water and wastewater systems such as pipe materials and tank design.
- Improve the Water Energy Sustainability Tool to include the life-cycle effects of electricity generation that accounts for the effects of mining, processing, and transporting fuel from its source to the point of combustion, and manufacturing and transporting all associated equipment.
- Evaluate demand management measures and compare them to water supply alternatives.
- Revise the Water Energy Sustainability Tool to consider additional air pollutants as well as water and land pollutants.

- Create a tool to analyze the energy demand of wastewater systems (Wastewater-Energy Sustainability Tool).
- Develop workshops for industry professionals.
- Improve material production analysis of certain materials that were not well-defined in the original tools, especially chemicals and plastics.
- Evaluate decentralized water and wastewater systems.
- Evaluate case studies to demonstrate the capabilities of Water Energy Sustainability Tool and the Wastewater Energy Sustainability Tool.

Conclusions and Recommendations

The project conclusions are presented in the following. Regarding the tools themselves:

- The Water-Energy Sustainability Tool has been revised to allow significantly more customization. Changes include allowing custom mixes of electricity generation sources, customizing the water sources or process scenarios that can be analyzed, adding the sludge disposal activity, and including emission factors for additional air, water, and land emissions.
- The Wastewater-Energy Sustainability Tool allows users to analyze wastewater systems using a life-cycle assessment perspective. The tool was designed to be more user-friendly than the Water-Energy Sustainability Tool. In particular, the Wastewater-Energy Sustainability Tool contains many default assumptions so users do not need as much detailed data to get a basic assessment of their treatment process. However, results will be improved if data entry is complete, accurate, and detailed.

None of the tools assess all environmental emissions, account for ecological effects, or quantify environmental impacts such as human toxicity. For water systems, it does not address the sustainability of supply (ensuring that recharge is equal to or greater than withdrawals). Though the assessment of sustainability for water and wastewater system is not complete, it does fill a gap by allowing utilities to capture an element of environmental sustainability that has been previously ignored.

Regarding the case study analyses:

- When small-scale decisions about pipes and tanks are analyzed, steel pipe and tanks tend to be environmentally preferable over other materials (for example, concrete and plastic).
- Custom electricity mixes, including additional renewable energy, can improve the environmental performance of water and wastewater systems. However, the impacts of renewable, or green, energy sources (for example, solar, wind, geothermal) are not zero, as is often assumed, if one includes the life-cycle impacts of the manufacture and transport of equipment for electricity generation.
- Sludge disposal tends to have little impact on the results for water and wastewater utilities. However, the disposal choice is one way that utilities can create "negative emissions"

(emission savings) for greenhouse gases and other air pollutants. Selecting landfills for disposal that use gas to produce electricity or incinerators with energy or heat recovery can reduce the systems' overall environmental impact, albeit marginally.

- Wastewater system results can be significantly improved by using methane to offset other electricity supplies. The plant in the case study is able to meet approximately 90 percent of its electricity needs using captured methane.
- Demand management or conservation programs can provide an inexpensive and environmentally preferable alternative to water supply. Converting to low-flow toilets, in particular, can provide significant savings when implemented statewide. Four strategies for conserving water outdoors are beneficial compared to water supply in this analysis: turf maintenance, xeriscaping, water pricing, and dormant turf.
- A desalination system can have a wide variety of impacts depending on the water source. In all cases, energy use is higher than alternative water supply.
- Case study results are site-specific and will vary by geography, hydrology, system design, water sources, and other factors. The case study results in this report can be used as guidance but may not be directly applicable to other utilities.
- Centralized water and wastewater treatment plants have lower energy requirements for a given amount of treated water relative to decentralized systems compared in this report through economies of scale.

Based on the outcomes and conclusions of this work, the following recommendations can be made:

- The Water Energy Sustainability Tool and the Wastewater Energy Sustainability Tool should be introduced to utilities to educate them about the tools themselves and, perhaps more important, about life-cycle thinking itself. Utilities should be encouraged to take a long-term and life-cycle perspective on energy use and emissions, including indirect emissions associated with the supply chain. Life-cycle assessment should be encouraged for design and planning of new water and wastewater systems and major system expansions and retrofits.
- Desalination is often discussed as an alternative for coastal water systems needing a reliable water source. However, the energy and environmental effects should be accounted for in decision-making. If implemented in several large cities, the impact of desalination on the state's energy supplies would be significant.
- Some wastewater treatment processes allow opportunities for heat and energy recovery that can offset fossil fuel consumption and prevent or lower greenhouse gas emissions. Anaerobic treatment processes, which produce methane, are particularly good candidates that should be considered.
- Water and wastewater systems that want to limit their environmental burden should carefully evaluate disposal choices. Offsets of fuel or electricity consumption as well as other

materials (for example, fertilizers) can be important to limiting the system's effect on the environment.

- Based on the interest in this research project at the two workshops conducted as part of this work to introduce industry personnel to the tools, the researchers and the California Energy Commission should try to keep the participants and other interested parties apprised of the latest research and tools available for evaluating these issues after this contract ends.

Water and wastewater design decisions are made based on several factors, including economic, engineering, and political concerns. Heretofore, the comprehensive and systemwide life-cycle environmental effects of the water infrastructure have not been a factor in these decisions. Generally, utilities, designers, and system planners are not aware that it is possible to assess the environmental effects of their systems using life-cycle assessment; as a result, the analysis is not included in decision-making.

For a more comprehensive picture of the costs associated with water supply choices, life-cycle assessment using the Water Energy Sustainability Tool, the Wastewater Energy Sustainability Tool, or similar method should be conducted routinely. This assessment would allow the industry to develop a comprehensive list of design recommendations for systems of differing parameters (for example, scale, water quality, process selection). The model and tools described in this report will allow utilities and other planners to incorporate these effects into their decision processes and strive for sustainable solutions with more informed analyses.

Benefits to California

Traditionally, the energy demand and associated environmental effects of the water infrastructure have not been a factor in water management decisions. The decision-support tools described in this report will allow utilities and other planners to assess the comprehensive and systemwide life-cycle consequences of alternative approaches to water management infrastructure and incorporate these effects and externalities into their decision processes, and with more informed analyses, strive for sustainable solutions.

CHAPTER 1: Introduction

The following report describes the methods, outcomes, and recommendations of the project "Life-cycle Energy Assessment of Alternative Water Supply Systems in California – Extensions and Refinements," CIEE Award No. MR-06-08. The project was completed by researchers at the University of California, Berkeley (UC Berkeley) on behalf of the California Energy Commission (CEC) between October 15, 2006 and December 31, 2010.

Some portions of the text of this report have been previously published in a similar format in the following papers (see list of references): (Stokes and Horvath 2006), (Stokes and Horvath 2009), (Stokes and Horvath 2010), and (Stokes and Horvath 2011).

1.1 Problem Significance

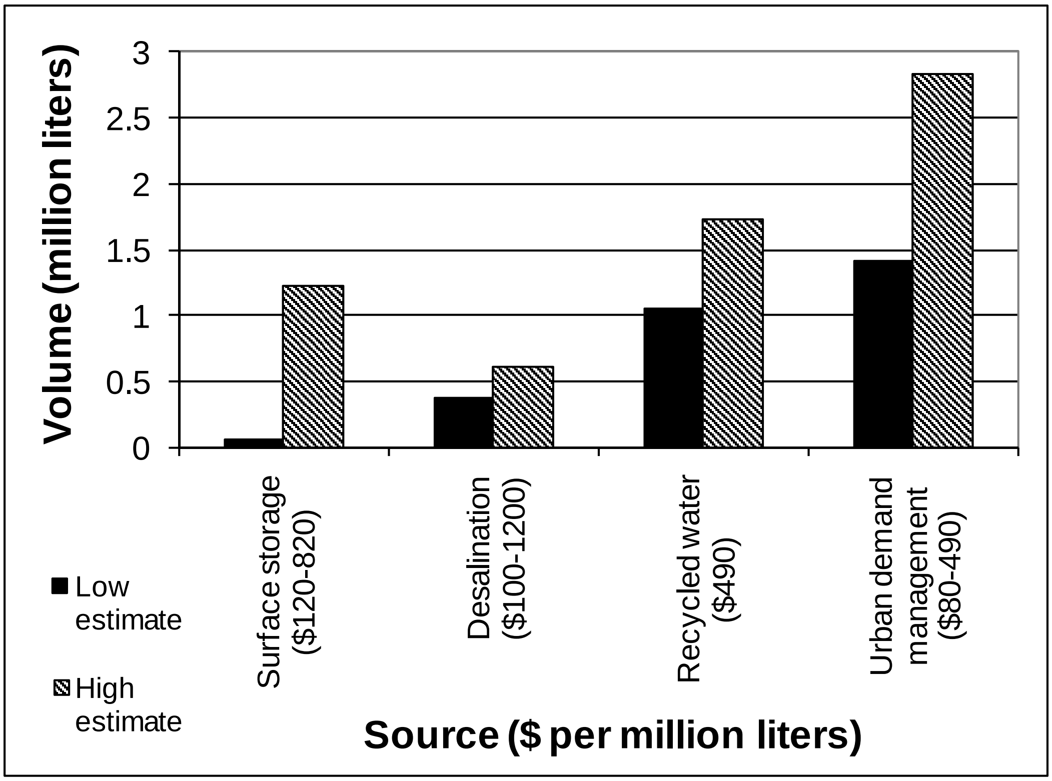
The scarcity of drinking water is a growing issue throughout many parts of the world, with 1.8 billion people located in areas likely to experience absolute water scarcity by 2025 (United Nations 2006). When relying solely on locally available freshwater, more than 40 percent of the world's population may face serious water shortages (Gleick et al. 2003). This scarcity may be due to climate, lack of infrastructure, political conflicts, or a combination of reasons.

The Western United States is especially sensitive to water scarcity. California consumes over six trillion liters of water annually for urban use. With California's population expected to grow by 14 million people by 2030, water demand will increase by 40 percent in the same period, based on 2000 water use rates (Hanak 2005). The more arid areas of the state will experience much of this growth, further exacerbating scarcity concerns (USBR 2003). Most water in arid areas is currently imported via a major conveyance network comprised of more than 4,800 km of pipelines, tunnels, and canals, and dozens of pump stations, such as the State Water Project (SWP; from the Sacramento/San Joaquin River delta) and the Colorado River Aqueduct (CRA). More than 18 percent of California's urban water use, as well as a significant volume of water for agricultural and environmental uses, is supplied via the CRA and the SWP, both of which may be adversely affected by climate change (Christensen et al 2004, Bennet et al 2004, Venrheenen et al 2004).

When traditional water sources fail to meet demand, alternatives need to be found. The current water supply system is already energy- and resource-intensive. Future alternatives will have even have higher energy and resource requirements and, consequently, environmental impacts. To develop a sustainable water system, these environmental implications should be incorporated into the water supply planning process.

Water and wastewater system sustainability incorporates a variety of considerations, including economic, engineering, social, and environmental issues. Past studies have proposed indicators for system sustainability in all categories [e.g., (Lundin and Morrison 2002; Sahely et al. 2006)]. The traditional engineering perspective only evaluates economic and engineering performance to determine system sustainability, though equity and other social issues can factor into some decisions [e.g., (Calijuri et al. 2005)]. Economically, obtaining water in dry areas is already expensive and costs will increase with scarcity. For example, brackish groundwater desalination can range in cost between $110 and $1,000 per 1,000 m^3 of water ($130 – $1,250 per acre-foot [AF]), and ocean desalination can cost $650 to $1,200 per 1,000 m^3 ($800 - $1,500 per AF) (Hanak 2005). Figure 1 depicts costs and potential volumes available for water sources in Southern California.

Figure 1: Production Potential and Costs for New California Water Supply



Source: Hanak 2005, California DWR 2005

The social and political implications of water scarcity have been discussed (e.g., in reference [Wolf 2007]) and can include water wars and transboundary conflicts between states. In the United States, conflicts occur between water providers, e.g., between the agriculture sector and urban utilities.

Environmental assessments are typically only applied to pre-existing environmental hazards and sensitive receptors in the area, such as human population, endangered species, and wetlands. Two major components of achieving water system environmental sustainability are often neglected. First, that water consumption occurs at or below the rate at which fresh water is returned to the source, so that these sources are not depleted. Second, the material and energy intensity of water infrastructure are minimized and can be continued long-term. The effects of excessive water consumption are site-specific, depending on climate, geography, hydrology, and ecology, and have been well discussed (e.g., [Calijuri et al. 2005; Hall et al. 2000]).

Conversely, minimizing the material and energy intensity of water infrastructure is an area of water sustainability that is more generalizable between diverse systems and provides the focus for this research.

The connection between water and energy use is strong. Water is used to produce energy (e.g., hydropower, solar thermal) and as an input to generation (e.g., cooling water). Water treatment and transport requires energy, which contributes significantly to the environmental effects of water. Pumping and treating urban water and wastewater consumes two to three percent of worldwide energy use (ASE 2002). This energy use is expected to grow by 33 percent over the next twenty-year period, as population growth increases demand for water and sanitation services. Broadly viewed, California's water-related services use approximately 19 percent of the state's electricity use and 30 percent of natural gas (CEC 2005; Navigant 2006). This energy use estimate includes aspects of water use not analyzed in this study such as agricultural water pumping and water heating by the consumer (CEC 2005). This connection, and the amount of electricity consumed, will grow as desalination or other energy intensive sources are adopted in water-scarce areas. Worldwide, desalination is considered a realistic water source in arid, coastal regions, including California, Florida, Mediterranean islands, and the Middle East. Desalination is not without critics, however (Dickie 2007), as it incurs considerable energy and environmental cost. The electricity used to supply water is the main source of greenhouse gases (GHG) from water provision, thereby contributing to the climate change problem.

Wastewater sustainability is also a concern. Changes to wastewater discharge requirements may increase the associated energy use. While wastewater treatment plants (WWTPs) are regulated to limit their impact on the environment, these regulations primarily address chemical concentrations in liquid effluent and solid waste. The broader effects associated with the wastewater system's life cycle are rarely considered, such as material production and use, infrastructure construction and maintenance, and energy production impacts.

Accounting for the environmental effects of material and energy intensity can inform water utility decision making when used in conjunction with conventional design criteria. While the environmental burden of infrastructure construction and maintenance as well as material production and delivery can be inconspicuous, the impact can be substantial. Water, sewer, district heating pipelines and similar infrastructure, for example, account for 10–20 percent of urban building mass (Herz and Lipkow 2002). Because the infrastructure in this country is aging, the U.S. Environmental Protection Agency (U.S. EPA) has estimated that nationwide capital spending to provide drinking water needs to be $334.8 billion over twenty years (USEPA 2009). A separate assessment estimates water and wastewater infrastructure needs an additional $107 billion in the next five years to be up-to-date (American Society of Civil Engineers 2009). The energy and materials used and the construction processes needed to install this infrastructure also increase a water or wastewater utility's life-cycle environmental effects.

Desalination plants, for example, are being considered by some coastal California utilities to provide a reliable and local water source. Adding solar power capacity is also being evaluated to reduce GHG emissions, without considering the emissions created upstream, during the manufacturing, installation, operation, and decommissioning of solar photovoltaic or concentrated solar power plants. The tool described in this report uses a life-cycle assessment (LCA) framework that allows a utility to more comprehensively compare all resulting greenhouse gas emissions in their decision process. The life-cycle assessment framework presented in this report can evaluate many other system-wide or process-specific decisions, such as selecting pipe materials, filters (conventional vs. membrane), disinfection processes, or different operational strategies.

Water and wastewater services are necessary for healthy life and will be provided even when the best available alternative is costly. However, system planners should aspire to minimize energy and material use and associated environmental effects. Accounting for energy and environmental effects in water planning requires LCA, a systematic methodology to account for energy and materials resource use and other environmental effects caused by extracting raw materials, manufacturing, constructing, operating, maintaining, and decommissioning the water supply infrastructure. Section 1.3 provides a more detailed discussion. Using LCA methodology, two MS Excel-based decision support tools, the Water-Energy Sustainability Tool (WEST) and the Wastewater-Energy Sustainability Tool (WWEST), were created to provide calculators of the energy and environmental implications of infrastructure associated with California's water and wastewater systems.

1.2 Problem Background

The Energy Commission's Public Interest Energy Research – Environmental Area (PIER-EA) project, "Life-cycle Energy Assessment of Alternative Water Supply Systems in California" CIEE Award No. MR-03-20 was funded in 2003-2004 to develop a methodology to analyze the energy and environmental effects associated with water supply infrastructure. The full details of that project are reported in Commission Publication CEC-500-2005-101. The original project was intended to be a broad-scope, screening-level analysis of water supply infrastructure. The goal of the initial study was to identify the most important parameters and provide focus for more detailed analyses. Therefore, the research proposed herein is intended to refine and expand the original work, making it more comprehensive, precise, and robust.

At the outset of the project, WEST specifically focused on three water sources: imported, recycled, and desalinated water. It analyzed the effects of four activities associated with energy and material use in infrastructure: material production, material delivery, construction and maintenance equipment use, and energy production in all life-cycle stages of the water supply system. WEST reported life-cycle effects in terms of gigajoules (GJ) of energy use and million grams (Mg) of air emissions, including GHGs reported in units of carbon dioxide equivalents (CO_2(e)), sulfur oxides (SO_x), particulate matter (PM), nitrogen oxides (NO_x), volatile organic compounds (VOC), and carbon monoxide (CO). Energy use and environmental emissions were reported for the water supply alternatives, life-cycle phases (construction, operation, and maintenance), and water supply functions (supply, treatment, and distribution). Two California case study systems were evaluated using WEST as a part of the original study, the Marin Municipal Water District (MMWD) and the Oceanside Water District (OWD). Information on WEST and prior research is available in Energy Commission's Publication 500-2005-10 (Stokes and Horvath 2005). Additional information about this phase of research is available in (Stokes 2004) and (Stokes and Horvath 2006). The work done prior to the start of this contract in 2006 will be referred to as Phase One work in this report.

In the following, tasks to extend, improve, and refine the water provision LCA methodology and WEST with the goal of making them more comprehensive, precise, and robust are described.

1.3 Project Overview

The tasks for this project were:

- Task 1: Administration. Task 1 consisted primarily of tracking project activities, reporting, and budgeting over the project period.
- Task 2: Assess alternative energy sources. The Phase One WEST tool assumed that the state average electricity mix was used in the analysis. For Task 2, WEST was edited to allow the user to enter customized electricity mixes, including options for renewable energy from solar, wind, biomass, and geothermal sources.
- Task 3: Consider additional water sources. After Phase One, the tool allowed only analysis of imported, desalinated, and recycled water. After Task 3's completion, the tool can be used to analyze other water sources or alternate scenarios (i.e., groundwater, surface water, or alternative treatment processes).
- Task 4: Calculate emission factors (EFs) for common materials. Task 4 evaluated the life-cycle emissions for common material choices in water supply systems, including pipe materials and tank design.
- Task 5: Include life-cycle effects of electricity generation. The Phase One version of WEST contained direct (i.e., smokestack) EFs for electricity use. Task 5 consisted of updating the EFs to allow the user to analyze their water systems using life-cycle EFs for electricity production, considering the effects of mining, processing, and transporting fuel from its source to the point of combustion and manufacturing and transporting all associated equipment.
- Task 6: Evaluate demand management measures. Task 6 quantified the effects of reducing water demand through conservation programs by evaluating the life-cycle impacts of water-efficient fixtures and appliances, rain collection systems, common irrigation systems in residential and commercial/industrial applications.
- Task 7: Consider additional pollutants. Task 7 expanded the pollutants analyzed by WEST beyond energy use, GHGs, and certain air pollutants included in Phase One. The revised tool evaluates additional air pollutants as well as water and land pollutants.

- Task 8: Develop workshops for industry professionals. Task 8 involved planning and presenting WEST and WWEST to industry professionals during two workshops, one in Southern California and one in Northern California.
- Task 9: Improve material production analysis. Task 9 improved the material production analysis by providing more detailed analysis of certain materials that are not well-defined using EIO-LCA, especially chemicals and plastics. Data for these improvements were obtained from publically- and commercially-available sources.
- Task 10: Analyze the energy demand of wastewater systems. A separate decision support tool, WWEST, was created and used to evaluate a case study system in Task 10.
- Task 11: Evaluate decentralized water and wastewater systems. WEST and WWEST were updated as needed to evaluate decentralized water and wastewater case studies. The results were compared to previously-evaluated centralized systems.

Since many of the tasks were interrelated, several deliverables and project outcomes do not fit neatly into a single task and are summarized below.

1.3.1 Tools

The final version of WEST and the associated user manual are included as Appendices A.1 and A.1.1, respectively. A list of revisions made to the tool since its original release is Appendix A.1.2. The WEST explanatory worksheets are presented in Appendix A.1.3.

The final version of WWEST and the associated user manual are included as Appendices A.2 and A.2.1, respectively. A list of revisions made to the tool since its original release is Appendix A.2.2. The WWEST Help worksheets are presented in Appendix A.2.

After publication of this report, updated versions of the tools and documentation will be available at: http://west.berkeley.edu/model.php.

1.3.2 Articles and Presentations

The following articles have been published as part of the research project. Due to copyright restrictions, the full text of these articles cannot be provided for public access on the internet and are therefore not included in this report.

- Stokes, J. R. and A. Horvath (2009). "Energy and Air Emission Effects of Water Supply." Environmental Science & Technology 43(8): 2680-2687. The paper can be found at: http://pubs.acs.org/doi/abs/10.1021/es801802h
- Stokes, J. and A. Horvath (2010). "Supply-chain Environmental Effects of Wastewater Utilities." Environmental Research Letters 5(1): 014015. The paper can be found at: 10.1088/1748-9326/5/1/014015
- Stokes, J. and A. Horvath (2011). " Life-Cycle Assessment of Urban Water Provision: Tool and Case Study in California." Journal of Infrastructure Systems 17(1): 15-24. This article can be found at: http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000036

In addition, the research was presented at several conferences. A copy of the slides used for each presentation is included in the appendix indicated.

- C. Facanha and J. Stokes (2007). "Sustainability of Infrastructure Systems." Chinese Institute of Engineers Conference, San Jose, Calif., February 11. (Appendix B.2.1)
- J. Stokes (2007). "Life-cycle Climate Change Effects of Water Supply Systems." American Water Works Association (AWWA) California-Nevada Section Conference, Sacramento, Calif., October 24. (Appendix B.2.2)
- J. Stokes (2007). "Life-cycle Environmental Evaluation of California Water Supply." Society for Environmental Toxicology and Chemistry - North America Annual Conference, Milwaukee, Wisc., November 9. (Appendix B.2.3)
- J. Stokes (2007). "The Life-cycle Climate Change Contributions of Water Systems." Presented to the Peninsula AWWA Monthly Meeting, Sunnyvale, Calif., December 5. (Appendix B.2.4
- J. Stokes (2008). "Energy Use and Greenhouse Gas Emissions of Wastewater Services: A Life-cycle View." AWWA California-Nevada Section Conference, Hollywood, Calif., April 24. (Appendix B.2.5)
- J. Stokes (2009). "A Cradle-to-Cradle Assessment of Energy and Climate Change Impacts of Recycled Water." WateReuse California Section Conference, San Francisco, Calif., March 23. (Appendix B.2.6)

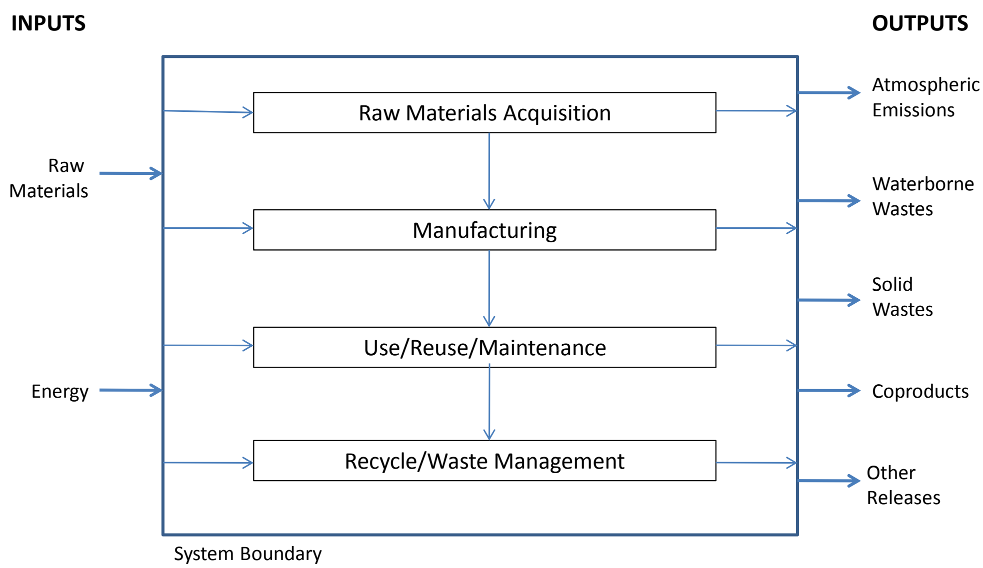
1.4 Literature Review

1.4.1 Life-cycle Assessment

The methodological framework of this study was LCA, a systematic, quantitative approach to evaluating the impacts of materials, products, processes, or services from "cradle" to "grave" (Graedel and Allenby 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 analysis was first described by the Society for Environmental Toxicology and Chemistry (SETAC) (SETAC 1991; SETAC 1993) and refined by the U.S. EPA in 1993 (Vigon 1993). The procedure was formalized by the International Organization of Standardization (ISO) 14040 series standards (ISO 1997; ISO 1998; ISO 2004). Figure 2 presents the LCA framework (US EPA 1993).

Process-based LCA requires data collection from various companies, government agencies, and published studies to evaluate the inputs and outputs to the system. 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 2005; Hendrickson et al. 1998; Hendrickson et al. 2006). As a general interdependency model, the economic input-output model describes interactions almost 500 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 principal investigator has been one of developers of the EIO-LCA model since 1995.

Figure 2: LCA Inventory Analysis Framework



Source: US EPA 1993

This research implemented a tiered hybrid LCA methodology (Suh and Huppes 2004) in this research, combining elements of process-based LCA and EIO-LCA. The hybridization is intended to take advantages of the strengths of each method while minimizing the disadvantages. The details of the hybridization are discussed in Chapters 9 and 10.

1.4.2 Water and Wastewater Life-cycle Assessment

Previous environmental LCAs of urban water and wastewater systems are limited to specific system components or are based on systems in other countries. A process-based LCA of the Belgian water cycle (pumping station to wastewater treatment) determined the effects of discharging untreated or marginally treated wastewater are more important than operational effects such as energy use (Lassaux et al. 2007). A second study evaluated water and wastewater services projected for 2021 in Sydney, Australia (Lundie et al. 2004) and concluded that demand management, energy efficiency and generation, and efficient biosolids recovery improved all environmental indicators, while other treatment alternatives produced mixed results for the indicators reported. The Australian study did not evaluate the construction process.

While these two studies considered both water and wastewater in the analysis, most are focused on one or the other. Table 1 provides a summary of findings from other key water LCAs. Table 1 also includes distinctions between those studies and the one presented in this report. Only one of the studies listed in Table 1 evaluated infrastructure in the United States (Filion et al. 2004) and none of the studies explicitly used a hybrid LCA approach.

Table 1: Water LCA Literature Summary

Reference	Summary
Herz & Lipkow 2002	RESULTS: Compared dig & no-dig installation for a variety of sewer & distribution pipe materials; no-dig installation reduced CO_2 emisisons by 20-30%; for water, lining pipes with mortar extended life & improved results
	DISTINCTIONS: Germany focus; process-based; evaluated only distribution system
Friedrich 2002	RESULTS: Compared treatment by conventional filters & membranes; either could be preferred depending on the indicator; electricity generation is dominant contributor to effects from both
	DISTINCTIONS: South Africa focus; GaBi-based; considered only treatment
Filion et al. 2004	RESULTS: Compared life cycle energy use of various pipeline replacement rates; a 50-year pipe replacement rate was recommended
	DISTINCTIONS: EIO-LCA-based; evaluated only distribution system
Raluy et al. 2005a,b	RESULTS: Compared desalination processes & importation; reverse osmosis (RO) is preferred to multi-stage flash & multi-effect desalination; environmental effects of importation were lower than RO given current technology
	DISTINCTIONS: Spain focus; SimaPro-based; does not analyze distribution system
Tangsubkul et al. 2005	RESULTS: Compared treatment for non-potable reuse by continuous microfiltration (CMF), membrane bioreactor (MBR), & wastewater stabilization pond (WSP); for all indicators, WSP produced the least emissions & CMF the most.
	DISTINCTIONS: Australia focus; GaBi with EIO-based analysis for construction; considered only water recycling treatment
Landu & Brent 2006	RESULTS: Evaluated water used for manufacturing; surface water withdrawals created most significant effects, followed by electricity generation
	DISTINCTIONS: South Africa focus; process-based; if present, analysis of construction phase not well-described
Friedrich et al. 2007	RESULTS: Emphasized the significant contribution of energy & electricity use; recommended electricity use as an indicator of environmental performance of South African water systems
	DISTINCTIONS: South Africa focus; inventory source not specified; considered local surface and recycled water
Racoviceanu et al. 2007	RESULTS: Evaluated water treatment focusing on chemical production, chemical transport, & plant operation; operational components were responsible for 94% of energy & 90% of GHG; 60% of operational burden was due to on-site pumping
	DISTINCTIONS: Canada focus; EIO-LCA-based; evaluated only treatment operation phase
Vince et al. 2008	RESULTS: Compared groundwater treatment, ultrafiltration, nanofiltration, ocean RO, and thermal distillation; electricity use for plant operation is the main cause of impacts; chemical production (lime, ozone, etc.) contribute significantly to results
	DISTINCTIONS: Europe focus; GaBi based; evaluated treatment processes only; did not specifically analyze infrastructure construction

Source: Adapted from (Stokes and Horvath 2009)

Table 2 provides a similar summary of wastewater-focused LCAs. As with the water studies, many of these LCAs are not comprehensive and none are United States-based.

Table 2: Summary of Wastewater LCA Literature

Scope and Source	Location and Findings Summary
S, T, D (Pasqualin et al. 2009)	Spain; Examined four biogas reuse options and five sludge disposal or reuse options; anaerobic treatment with biogas used for electricity/heat and a combination of sludge reuse for land application and in cement making are preferred
S, T, D (Murray et al. 2008)	China; Explored sludge reuse options (as fertilizer and in concrete); anaerobic treatment most environmentally benign, incineration most economically and environmentally costly
L, S, T (Monteith et al. 2005)	Canada; Analyzed onsite treatment at WWTP; GHG emissions range from 0.14 to 0.63 kg CO_2eq/m^3
L, S, T (Sahely et al. 2006)	Canada; Evaluated GHGs due to liquid and sludge treatment; wastewater treatment in Canada was responsible for 1 Tg CO_2eq in 2000
S, T, D (Houillon and Jolliet 2005)	France; GHGs are lowest for cement kiln incineration and highest for landfill and agricultural spreading
L, S, T, D (Palme et al. 2005)	Sweden; Sludge disposal alternatives considered had different nutrient and energy recovery efficiencies; agricultural spreading is environmentally preferable
L, S, T, D (Lundie et al. 2004)	Australia; WWTPs contribute 41% of energy use and 49% of GHGs in the full water cycle; biosolid disposal by land application is enviromentally preferred
L, S, T (Beavis and Lundie 2003)	Australia; Analyzed disinfection and digestion options; UV has highest environmental costs; energy use and GHGs are lower for anaerobic than aerobic digestion but results are mixed for other emissions
L, S, T (Keller and Hartley 2003)	Australia; Evaluated case studies with aerobic or anaerobic digestion; combining activated sludge and aerobic digestion creates highest GHGs; processes that captured methane for use in electricity production have lowest emissions
S, T, D (Suh and Rousseaux 2002)	France; Explored treatment, stabilization, and sludge disposal; resource depletion lowest for incineration and landfilling; anaerobic digestion with land application has lowest climate change and overall weighted results

ABBREVIATIONS: CO_2eq= carbon dioxide equivalents; D= disposal; GHG= greenhouse gas; L= liquid; S= sludge; T= treatment; Tg= Teragrams; UV= ultraviolet disinfection; WWTP= wastewater treatment plant

Source: Adapted from (Stokes and Horvath 2010)

1.5 Structure of Report

This report is structured by tasks, as listed above. The discussion of each task, excluding Task 1, contains a section on the Project Approach, Project Outcomes, and Conclusions and Recommendations. Task 1, Administration, is not specifically addressed in this report. A summary section follows Task 11 and summarizes overall project outcomes, conclusions, and recommendations.

CHAPTER 2:
Task 2 – Assess Alternative Energy Sources

After the Phase One work, WEST allowed the user to select the state where the water system is located from a drop-down menu. Emission factors, obtained from the U.S. EPA's Emissions and Generation Resource Integrated Database (EGRID) were used to assess the environmental effects of electricity generation (EGRID 2002). These factors are based on statewide average emissions for fossil fuel combustion. WEST was designed this way because electricity, once on the grid, is no different regardless of where or how it was generated.

However, a utility may want to analyze site-specific energy mixes or explore the use of alternative sources. Users can specify in WEST the proportion of different electricity mixes they use to operate their systems (e.g., 70 percent nuclear, 10 percent solar, and 20 percent natural gas). Representative EFs for several energy sources were included in the tool for guidance. However, the user can also enter site-specific EFs in grams of emissions per kilowatt-hour (g/kWh). Utilities can obtain results which reflect their atypical electricity sources. It also allows the assessment of "green" alternatives or a local (utility-specific) energy mix.

The use of the tool was demonstrated by comparing the environmental effects of desalination powered by "green" energy to desalination using average emissions. Several publications discuss the possibility of pursuing desalination using "green" power as an alternative for water supply in arid areas (Gleick 1995).

2.1 Task 2 Approach

2.1.1 Revisions

As part of this task, WEST was revised to allow customized energy analysis primarily for electricity sources (See Appendix C.1 for more information.). Specifically, the completed WEST revisions included:

- Modifying the electricity production data entry pages to allow the users to select whether they want to use the default state average emissions, a user-defined generation mix, or user-defined EFs.
- Using the EGRID source ([USEPA 2002]; year 2000 data) and technical documentation to estimate state-specific EFs for eight electricity generation sources (coal, oil, natural gas, nuclear, hydroelectric, solar, biomass, and 'other fossil fuels'). U.S. EPA assumes that there are no emissions from wind and geothermal production.
- Updating the data entry pages to allow the user to estimate the transmission and distribution losses for each of the electricity sources. These losses were previously neglected. WEST uses a default value of 7 percent, the national average for system losses, for all electricity sources (CBO 2003).

The researchers also prepared associated documentation. The explanatory pages for the energy production module of WEST are included in Appendix A.1.3; this page is hyperlinked to the data entry and calculation pages within WEST to provide instantaneous help to the user.

2.1.2 Case Study Description

The case study is a desalination plant serving a hypothetical city in coastal California. The water utility obtains approximately 10,000 AF per year from desalinated seawater. Desalinated water is obtained from a low-salinity seawater source (similar to the San Francisco Bay). The total dissolved solids concentration of this water source is approximately 30,000 milligrams per liter (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) specifications. Because the RO process has a 50 percent recovery rate, 20 million gallons per day (MGD) of seawater are extracted to produce 10 MGD, or 10,000 AF per year of potable water. Constructing off-site infrastructure necessary to develop the plant site (e.g., roads, sewer, power) is excluded from the analysis. Additional information about the desalination case study is included in Appendix C.2.

To demonstrate the new capabilities of WEST, the authors analyzed four alternative electricity mix scenarios. These scenarios were:

1. the California state average electricity mix (estimated from EGRID data);
2. the national average electricity mix (estimated from EGRID data);
3. 50 percent solar energy with the remainder of electricity from the California average mix; and
4. 80 percent "green" electricity (20 percent nuclear, 15 percent biomass, 15 percent wind, 20 percent solar, and 10 percent geothermal) with the remainder of electricity from the California average mix.

Table 3 summarizes data related to the electricity mixes analyzed for this task as well as the EFs used for the various electricity sources. All of the scenarios used the same assumed values for transmission and distribution losses for each source. For sources which are produced at large plants assumed to be located far from the water system (coal, oil, natural gas, and nuclear), losses of 10 percent were assigned, more than the national average loss of approximately 7% but within a realistic range. Other sources were assigned losses of 2 percent or 5 percent depending on their assumed distance from the water system. Only EFs which vary between electricity sources are included in the table.

Table 3: Desalination Scenario Descriptions

	Calif. Average Generation Mix	Mix Contributions and Source-Specific Emission Factors									
		Coal	Oil	Natural Gas	Nuclear	Other Fossil Fuels	Hydro	Biomass	Wind	Solar	Geo-thermal
Energy Mix											
Scenario 1	--	1.1%	1.4%	49.6%	16.9%	1.5%	18.8%	2.9%	1.7%	0.3%	5.9%
Scenario 2	--	51.7%	2.8%	15.9%	19.8%	0.6%	7.1%	1.5%	0.2%	0.0%	0.4%
Scenario 3	50%	0%	0%	0%	0%	0%	0%	0%	0%	50%	0%
Scenario 4	20%	0%	0%	0%	20%	0%	0%	15%	15%	20%	10%
Assumed Distribution Loss	10%	10%	10%	10%	10%	5%	5%	2%	5%	2%	5%
Emission Factors (g/kWh)											
GHG	287	965	1074	515	0	195	0	23	0	217	0
NO_x	0.26	3.03	2.73	0.32	0	0.93	0	0.79	0	0.24	0
SO_2	0.08	3.08	3.31	0.01	0	0.42	0	0.04	0	0.004	0

2.2 Task 2 Outcomes

Data for the hypothetical desalination case study and the four electricity mix scenarios were entered into the revised WEST. Results for energy production in the operation phase were affected by the revisions. Table 4 shows energy production and overall results.

Table 4: Desalination Scenario Results

	Energy Production Results			Total Results		
	Supply	Treatment	Distribution	Supply	Treatment	Distribution
(Results in million grams (Mg) and as percentage of Scenario 1 result.)						
Scenario 1: State Average Electricity Mix						
GHG	3200 / --	10,000 / --	3500 / --	3200 / --	13,000 / --	3500 / --
SO_x	0.87 / --	2.8 / --	1.0 / --	1.1 / --	15 / --	1.1 / --
NO_x	2.9 / --	9.2 / --	3.1 / --	3.1 / --	21 / --	3.4 / --
Scenario 2: National Average Electricity Mix						
GHG	6700 / 210%	21,000 / 210%	7400 / 210%	6800 / 210%	24,000 / 190%	7400 / 210%
SO_x	19 / 2100%	59 / 2100%	20 / 2100%	19 / 1800%	72 / 470%	21 / 1800%
NO_x	19 / 660%	60 / 650%	21 / 660%	19 / 610%	72 / 340%	21 / 610%
Scenario 3: 50% Solar, 50% State Average Mix						
GHG	2500 / 81%	8100 / 81%	2800 / 81%	2600 / 81%	11,000 / 85%	2800 / 81%
SO_x	0.42 / 49%	1.4 / 49%	0.46 / 48%	0.61 / 58%	14 / 91%	0.65 / 57%
NO_x	2.5 / 89%	8.1 / 89%	2.8 / 89%	2.8 / 90%	20 / 95%	3.0 / 89%
Scenario 4: 80% Green Mix, 20% State Average Mix						
GHG	1100 / 34%	3500 / 34%	1200 / 34%	1100 / 35%	6400 / 49%	1200 / 35%
SO_x	0.24 / 28%	0.78 / 28%	0.26 / 28%	0.43 / 40%	13 / 87%	0.45 / 39%
NO_x	2.3 / 79%	7.3 / 79%	2.5 / 79%	2.5 / 81%	19 / 91%	2.8 / 81%

The results indicate that using the national average electricity mix (Scenario 2), including a significantly higher percentage of coal generation, increases the final results dramatically. Using "green" electricity sources can substantially reduce overall life-cycle air emissions. Scenario 4 results were between 13 percent and 60 percent lower than Scenario 1 results. GHG emissions associated with solar energy might be expected to be lower in the Scenario 3 results. However, the EF for GHG emissions from solar energy (217 g/kWh) is similar to the emissions associated with California's state electricity mix (287 g/kWh). The solar electricity EF is calculated using U.S. EPA data from eleven solar plants located in California, all of which emit relatively high amounts of GHGs (USEPA 2002). The sources of these emissions, as well as emissions for other sources commonly assumed to be emission-free (e.g., nuclear and hydropower), is not certain. However, a review of EGRID data indicates it may be primarily due to the use of generators at the plant. Steam-turbine generators are apparently used at several solar plants in California. The emissions associated with the generators are estimated using AP-42 EFs (EPA 2001).

The "green" energy scenario results show a greater reduction for two reasons: 1) a higher percentage of alternative energy is used and 2) increased use of zero-emission sources or essentially zero-emission sources, including wind, geothermal, nuclear, and hydroelectric energy. However, it is important to note that only direct emissions (i.e., "smokestack" emissions) are included in EGRID; the life-cycle emissions associated with these sources are not included in these EFs. The life-cycle emissions for "green" sources might still be lower than fossil fuel sources, but they will not be zero. Life-cycle EFs for energy sources were later added to WEST during Task 5 of this project and were not reflected in the discussion above.

2.3 Task 2 Conclusions and Recommendations

The Task 2 revisions to WEST provided an important degree of customization to the results. Many utilities are considering various means of providing electricity to reduce their environmental effect. These revisions, in conjunction with those that will be later discussed in Task 5, makes WEST a more robust and useable tool for many California users.

In addition, the results of the case study analysis show that the energy mix selection can make a significant difference in the operational effects of a water system. However, the solar energy EFs also indicate that electricity sources perceived as zero-emission are not truly so in practice. Analyses of electricity alternatives should reflect this distinction. Task 5 further explores the emissions for different energy sources. Please refer to the Chapter 5 Outcomes and Conclusions for a more complete discussion of these issues.

CHAPTER 3:
Task 3 – Consider Additional Water Sources

At the end of Phase One work, WEST accounted for water from importation (surface water sources located outside the utilities' service areas), ocean water, saline aquifers, and recycled water. The Task 3 update allows the user to assess other sources of water, including local surface water or groundwater. In addition, the user can define other scenarios for analysis, such as alternate treatment processes, operating strategies, or pipeline designs.

3.1 Task 3 Approach

3.1.1 Revisions

As part of this task, WEST was revised to allow customized alternatives to be analyzed. Specifically, WEST data entry and results worksheets were updated to allow evaluation of up to five water sources. Five default sources are provided: imported water, desalinated water, recycled water, local groundwater, and local surface water. However, the user can customize these as desired. With this structure, WEST could be used to assess different treatment plants, alternative designs for water storage, alternative systems, or other alternatives. Appendix D contains more information on these and other Task 3 revisions.

3.1.2 Case Study Description

To demonstrate the new capabilities of WEST, a system was analyzed which uses imported water, recycled water, and local reservoir water. The case study is based on an unnamed utility in Northern California. Two scenarios were considered: the system as it currently operates and a proposed scenario to replace imported water with desalinated water. The data used in this analysis were publicly available, provided by the utility for a prior study (Stokes and Horvath 2004), or estimated based on values in the literature (Stokes 2004). Detailed information about the case study can be found the Phase One final report (Horvath 2005).

3.2 Task 3 Outcomes

The deliverables for Task 3 were: 1) updated WEST which includes the ability to analyze all water sources, 2) documentation of calculations, assumptions, and WEST operation, and 3) results from evaluating a previously-analyzed Northern California case study while considering the local reservoirs which provide the majority of the system's water. The reservoirs were not included in the original analysis. A final version of WEST is included as Appendix A.1. The final documentation, including the revisions from this task, is provided in Appendix A. The results for the case study assessment are discussed below.

Table 5 shows results for the four system sources: imported water, desalinated water, recycled water, and local reservoirs. Energy use and emissions are reported as GJ and Mg per 100 AF of water from each source, respectively.

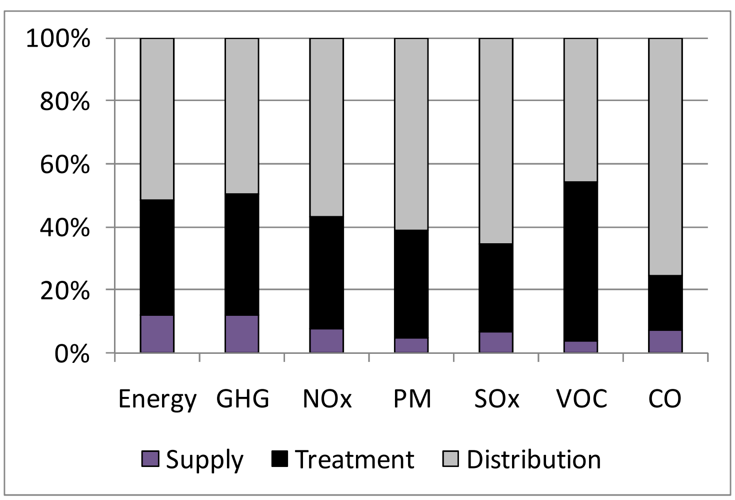
Table 5: Summary of Results for the Water Sources Comparison Study

Environ-mental Effects	Results (Energy: GJ/100AF; others: Mg/100 AF)			
	Water Source			
	Imported	Desalinated	Recycled	Local Reservoirs
Energy	1900	4600	1300	2200
GHG	140	350	12050	150
NO_x	0.37	0.73	0.17	0.46
PM	0.067	0.11	0.026	0.11
SO_x	0.36	0.71	0.090	0.54
VOC	0.084	0.26	0.027	0.15
CO	0.52	0.74	0.10	0.69

Desalinated water uses the most energy and produces the most GHG. The results for imported water and local reservoir water are comparable for all categories. For emissions of other air pollutants, shown in Figure 3, the results varied. Desalination produced the most NO_x. Reservoir water produced the most SO_x, VOCs, and CO. The differences are largely due to the different sources of emissions. For desalination, energy production was most significant. Material production generally contributed most to the emissions from reservoirs.

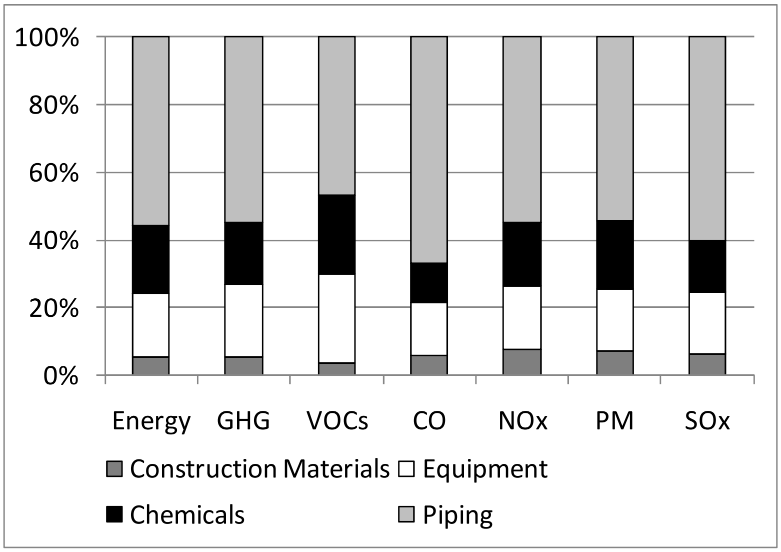
Figure 3 shows the breakdown of the results for the utility by water supply phase (supply, treatment, or distribution). The figure shows that for the water sources used by this utility, distribution dominates the results. For this utility, the distribution system is exceptionally expansive and energy-intensive. The service area's topography is very hilly and, as a result, the communities served by the utility are spread out.

Figure 3: Results by Water Supply Phase



In addition, Figure 4 shows that for material production, piping produces the most environmental effects, contributing more than half of the effects for all emissions. Details about piping use are summarized in Appendix D. Piping includes the pipes themselves and all associated equipment (e.g., valves, fittings, flowmeters).

Figure 4: Material Production Results by Material



The utility provided an electricity cost and consumption estimate for 2004 of $3.6 million and 26,000 megawatt-hours (MWh), respectively. The number was provided verbally and no documentation was provided. The authors used estimates of the number of pumps in the systems and average horsepower to distribute the consumption between different water sources and water supply phases. The assumptions used are described in Appendix D.

To check the results, the authors used estimates of water-related energy use from (Navigant 2006) and adjusted them based on the utility conditions (e.g., the imported treatment process is simple and will use significantly less than the median of 100 MWh per million gallons [MG]) presented in (Navigant 2006). Table 6 includes a revised estimate of the expected energy use.

For imported supply, the original estimate was provided by the utility's upstream water suppliers and therefore remains unchanged. Desalination electricity consumption values were not changed as they were based on pilot testing, as reported by the utility. Overall, the revised estimates were higher, especially in the cases of reservoir and recycled water. These revised estimates produce the results shown in Table 7.

Table 6: Electricity Consumption Estimates for the Northern California Utility

Water Supply Phase	Original Assumed Annual Electricity Use (MWh)[1]	Selected Electricity Use Factor (kWh/MG)[2]	Revised Annual Electricity Use (MWh)
Reservoir Supply	935	400	2,895
Reservoir Treatment	1,040	1,000	7,237
Imported Supply[3]	9,800	--	9,800
Imported Treatment	25	100	264
Potable Distribution	22,110	1,200	15,022
Recycled Supply	390	10	2
Recycled Treatment	165	50	11
Recycled Distribution	1,325	1,200	274
Desalination Supply[4]	3,795	--	3,795
Desalination Treatment[4]	38,460	--	38,460
Desalination Distribution[4]	24,330	--	24,330

[1] From (Stokes 2004). The utility provided the annual electricity use as 26,000 MWh, exclusive of imported supply and proposed desalination system. The breakdown among water sources was assumed based on pump capacities.

[2] Based on range of values provided in source: (Energy Commission 2005)

[3] Electricity use for imported supply was provided by neighboring utilities in exact values and was not adjusted.

[4] Desalination electricity use was based on pilot studies and was not adjusted.

Table 7: Source Results for Revised Electricity Use

Environ-mental Effects	Results (Energy: GJ/100AF; others: Mg/100 AF)			
	Water Source			
	Imported	Desalinated	Recycled	Local Reservoirs
Energy	1400	4500	450	1700
GHG	110	340	50	130
NO_x	0.34	0.73	0.11	0.37
PM	0.067	0.12	0.026	0.087
SO_x	0.35	0.71	0.071	0.43
VOC	0.084	0.26	0.027	0.088
CO	0.51	0.74	0.084	0.60

Because the estimates of electricity use for the potable distribution system were reduced while supply and treatment estimates generally increased, the results for imported, desalinated, and local reservoirs were not significantly changed. However, the results for recycled water are significantly lower than the original estimates. The authors feel these revised results for recycled water are more indicative of the actual recycled water environmental effects.

This revised work indicates that material production is still a significant contributor to the final results. For imported water, it is more important than energy production. Prior studies have indicated that energy production is significantly more important than material production. The results of this analysis ultimately may not be contradictory. Currently, only the direct emissions associated with energy production are included in WEST. Including the life-cycle effects of mining, transporting, and processing fuels will increase overall results for energy production. Chapter 5 discusses the outcomes of including the life-cycle effects of electricity generation.

Tables 8 and 9 provide results for the overall utility system using the revised electricity assumptions. Table 8 provides results for the current system, with water that is imported from a surface water source 30 miles away (26 percent), recycled from wastewater plant effluent (2 percent), and collected in local reservoirs (72 percent). The results for the utility's proposed system, which replaces imported water with desalinated water, are shown in Table 9.

Table 8: Results for Current Utility Water Mix (importation, no desalination)

Environ-mental Effect	Results (Energy: GJ/100 AF; Others: Mg/100 AF)									
		Life-cycle Phase			Water Supply Phase			Water Source		
	System Total	Con-struction	Oper-ation	Mainten-ance	Supply	Treat-ment	Distri-bution	Import	Recycle	Local Reservoir
Energy	2100	280	490	1300	300	450	1300	490	30	1500
GHG	150	20	38	91	23	31	96	37	2.7	110
NO_x	0.43	0.077	0.052	0.3	0.051	0.10	0.28	0.098	0.0039	0.33
PM	0.13	0.049	0.0029	0.078	0.042	0.03	0.057	0.017	0.033	0.079
SO_x	0.48	0.087	0.018	0.037	0.054	0.10	0.32	0.093	0.0020	0.038
VOC	0.13	0.019	0.0065	0.10	0.010	0.052	0.065	0.022	0.00061	0.011
CO	0.63	0.12	0.021	0.48	0.079	0.082	0.47	0.14	0.0023	0.049

Table 9: Results for Proposed Utility Water Mix (desalination, no importation)

Environ-mental Effect	Results (Energy: GJ/100 AF; Others: Mg/100 AF)									
		Life-cycle Phase			Water Supply Phase			Water Source		
	System Total	Con-struction	Oper-ation	Mainten-ance	Supply	Treat-ment	Distri-bution	Desal-inate	Recycle	Local Reservoir
Energy	2800	300	940	1500	230	1200	1300	1200	30	1500
GHG	200	22	74	110	17	89	98	90	2.7	110
NO_x	0.53	0.082	0.082	0.36	0.046	0.20	0.28	0.19	0.0039	0.33
PM	0.14	0.05	0.0037	0.088	0.042	0.043	0.058	0.03	0.033	0.079
SO_x	0.57	0.095	0.033	0.44	0.055	0.19	0.33	0.19	0.0020	0.38
VOC	0.17	0.022	0.0067	0.14	0.011	0.096	0.066	0.067	0.00061	0.11
CO	0.69	0.13	0.035	0.52	0.08	0.14	0.47	0.19	0.0023	0.49

Overall, the proposed system, which uses energy-intensive desalination as a source, creates approximately 25 percent higher environmental effects. More GHGs are emitted by the proposed system in the operation phase and the treatment phase due to the energy used in the desalination treatment process. Distribution system effects are also marginally higher due to additional pipelines needed to connect the desalination plant to the existing distribution system. Table 3.5 shows that desalination and local reservoir results are similar. However, the reservoirs provide almost three times more water to the overall system.

3.3 Task 3 Conclusions and Recommendations

The work completed as part of Task 3 will allow WEST users more flexibility in analyzing a variety of water supply scenarios and utility operation plans. The authors hope the ability to conduct a more customized analysis will increase the number of potential users for the tool.

The case study analysis of a Northern California utility shows that local water sources and imported water sources produce similar results. With the revised electricity use estimates, recycled water is shown to be less environmentally intensive than other alternative sources, approximately one-third of local water results for most emissions. The impacts due to desalination are much higher, in some cases three times higher than local water results.

CHAPTER 4:
Task 4 – Calculate Emission Factors for Common Materials

Task 4 was designed to assess certain common components of water systems and identify EFs which can be used to distinguish between material choices.

4.1 Task 4 Approach

For Task 4, the researchers created a new tool, WESTLite, a simplified version of WEST. The tool can be found in Appendix E.1. WESTLite allows the user to do simplified analyses of pipe and tank alternatives. Pipe and tank analyses both have separate data entry and results pages. For both pipe and tank analyses, the user can define the analysis period. Both analyses are based primarily on EIO-LCA EFs (CMU 2005). However, EIO-LCA does not allow the user to distinguish between different materials within a product category (e.g., steel and iron pipe, polyethylene (PE) vs. polyvinyl chloride (PVC) pipe). The EFs needed to distinguish between these materials are collected as part of Task 9. The tank analyses also use electricity EFs from the U.S. EPA (EGRID 2002). The differences between the pipe and tank analyses are discussed in the following sections.

4.1.1 Pipe Analysis Approach

For the pipe analysis, the user can select up to 5 different pipe diameters (in inches [in.]) to be simultaneously analyzed, including 2, 6, 12, 18, 24, 30, 36, 48, 60, and 72. For each of the four pipe materials considered by WESTLite (PVC, concrete, ductile iron [DI], and steel), the user can define the service life and the length of each pipe segment. For concrete, DI, and steel pipe, the user may define whether the pipe will be mortar-lined; for DI and steel pipe, the user may choose to analyze coated pipes and may select the coating material. For DI pipe, the coating options are asphalt or PE tube. For steel pipe, the coating options are epoxy, tape, or PE tube. Figure 5 shows an example data entry page. Yellow cells indicate values the user must enter; pink cells indicate the user must select from a drop-down menu. Hyperlinks refer the user to information in the explanatory Help worksheet. The equations used in WESTLite are outlined in Appendix E.2.

Figure 5: WESTLite Pipe Data Entry Worksheet

Go to Input Key
Go to Piping Input Documentation
Go to Piping Analysis Assumptions

General Data

Length of pipe considered	100	feet
Analysis Period	75	years

Pipe Diameter

6	inches
12	inches
24	inches
36	inches
60	inches

Pipe Improvement Options Table

	Mortar lining	Coating	Coating Selection
PVC			
DI	No	No	
Concrete	No		
Steel	No	No	

Pipe Details Table

	Service Life (yr)	Pipe Segment Length (ft)
Plastic	60	25
DI	75	18
Concrete	75	30
Steel	75	40
Gaskets	20	
Mortar lining	75	
Coating	75	

Reset Default Values

4.1.2 Tank Analysis

For the tank analysis, the user can analyze tanks made of three materials: concrete, steel, and wood. Steel tanks can be either ground-level or elevated. The following tank capacities in million gallons (MG) can be analyzed for each of the four tank alternatives: 0.005, 0.1, 0.25, 0.5, 0.75, 1, 2, 4, 5, 6, 8, and 10. The default tank capacity is 1 MG. The user can also define the service life of the foundation (default: 75 year). For each tank alternative, the user may define the service life (years) and the tank diameter (feet). Figure 6 shows a sample data entry page for the tank analysis. Hyperlinks refer to information in the explanatory Help worksheet. The equations used in WESTLite are outlined in Appendix E.2.

Figure 6: Tank Analysis Data Entry Worksheet

Go to Input Key
Go to Tank Input Documentation
Go to Tank Analysis Assumptions

Analysis Period	75	years
Tank Capacity	1	MG
Foundation Life	75	years

Tank Details

Tank Type	Service Life (years)	Tank Height (feet)	Foun-dation Thickness (feet)	Tank Config-uration	Electricity Mix [Select State]	Additional Annual Electricity Use [kWh]	Additional Pipe Required (ft)
Concrete	75	15	2.5	Below grade line			
Steel, ground level	75	12	2	Below grade line			
Steel, elevated	75		2	At grade line			
Wood	40	10	2	Below grade line			

Suggested electricity use per unit flow and head [kWh/ (gal/min) / foot] = 1.4

Assumptions about tank foundation size and electricity use can be reviewed and edited on the "Tank Analysis Assumptions" worksheet.

Reset Default

4.2 Task 4 Outcomes

The results for pipe and tank analyses are summarized below.

4.2.1 Pipe Analysis Outcomes

The outcomes of the pipe analysis are described in this section. A typical summary results page is shown in Figure7. The results correspond to the input shown in Figure 5. Additional analysis assumptions are summarized in Appendix E.3.

Figure 7: Pipe Analysis Results Worksheet – Summary Results

Results

Go to Pipe User Input
Go to Pipe Calculations Documentation

VIEW ALL RESULTS | VIEW SUMMARY RESULTS

General		Total						
Diameter (in)	Material	Energy (MJ)	GHG (g)	CO (g)	NO_x (g)	PM10 (g)	SO_x (g)	VOC (g)
6	PVC	10944	814405	6827	1985	247	1864	1713
	DI	8166	570107	3648	1887	431	2416	557
	Concrete	0	0	0	0	0	0	0
	Steel	0	0	0	0	0	0	0
12	PVC	23879	1751457	14180	3942	569	4151	3598
	DI	20784	1433578	8956	4719	1035	5841	1530
	Concrete	37928	2635124	14467	8530	1572	10579	1795
	Steel	0	0	0	0	0	0	0
24	PVC	92052	6823698	56678	14864	2107	15763	14266
	DI	51708	3567763	22304	11746	2580	14553	3800
	Concrete	81142	5637624	30950	18250	3364	22633	3839
	Steel	27102	1924460	12717	6421	1542	8593	1637
36	PVC	153257	11339264	93761	24847	3534	26315	23634
	DI	99523	6876326	43105	22654	4998	28177	7253
	Concrete	103994	7224846	39663	23387	4310	29000	4926
	Steel	40653	2886690	19075	9632	2314	12890	2455
60	PVC	0	0	0	0	0	0	0
	DI	0	0	0	0	0	0	0
	Concrete	232122	16127190	88536	52205	9622	64742	10986
	Steel	133816	9502021	62789	31706	7616	42429	8082

RESULTS STATISTICS

Among pipes of similar materials, the average GHG results breakdown for production is:

Material	Pipe	Gasket	Lining	Coating
PVC	88%	12%	0%	0%
DI	72%	28%	0%	0%
Concrete	99%	1%	0%	0%
Steel	100%	0%	0%	0%

Among pipes of similar size, the average GHG results breakdown for production is:

Diameter	Pipe	Gasket	Lining	Coating
6	88%	12%	0%	0%
12	87%	13%	0%	0%
24	90%	10%	0%	0%
36	88%	12%	0%	0%
60	100%	0%	0%	0%

To demonstrate the capabilities of WESTLite, the researchers compared different pipe alternatives for five different pipe diameters (in inches) common in water transmission and distribution systems (6, 12, 24, 36, and 60). The analysis compares the purchase of 100 feet of the relevant material over a 75-year period. Valve and fitting requirements for the materials are similar and therefore were excluded from the analysis. Emission factors for these scenarios, including a variety of pipe linings and coatings, are included in Table 10; Table 11 shows the breakdown of components (i.e., pipe, gaskets, lining, coating) for two diameters of pipe (24 in. and 36 in.). Figure 8 shows the relative energy consumption of the considered scenarios.

Table 10: Emission Factors per 100 feet of Pipe

General		Pipe and Gaskets Only			Mortar lined, no coating			Mortar lined, Coating (DI and Steel: PE Tube)		
Diameter (in)	Material	Energy (MJ)	GHG (Mg)	SO_x (g)	Energy (MJ)	GHG (Mg)	SO_x (g)	Energy (MJ)	GHG (Mg)	SO_x (g)
6	PVC	11,000	0.81	1,900	--	--	--	--	--	--
	DI	8,200	0.57	2,400	8,200	0.57	2,400	9,600	0.68	2,700
12	PVC	24,000	1.8	4,200	--	--	--	--	--	--
	DI	21,000	1.4	5,800	21,000	1.4	5,800	23,000	1.6	6,300
	Concrete	38,000	2.6	11,000	38,000	2.6	11,000	--	--	--
24	PVC	92,000	6.8	16,000	--	--	--	--	--	--
	DI	52,000	3.6	15,000	52,000	3.6	15,000	60,000	4.2	16,000
	Concrete	81,000	5.6	23,000	81,000	5.6	23,000	--	--	--
	Steel	27,000	1.9	8,600	27,000	1.9	8,600	35,000	2.5	9,900
36	PVC	150,000	11	26,000	--	--	--	--	--	--
	DI	100,000	6.9	28,000	100,000	6.9	28,000	110,000	8.0	31,000
	Concrete	100,000	7.2	29,000	100,000	7.2	29,000	--	--	--
	Steel	41,000	2.9	13,000	41,000	2.9	13,000	56,000	4.0	15,000
60	Concrete	230,000	16	65,000	230,000	16	65,000	--	--	--
	Steel	130,000	10	42,000	130,000	9.5	42,000	170,000	12	49,000

Table 11: Data Analysis for 24-in. and 36-in. Pipe

Diameter (in)	Material	Lining	Coating	Energy (MJ)	Percentage of Total Energy Use from Production			Coating			
					Pipe	Gasket	Lining	Asphalt	Epoxy	PE tube	Tape
24	PVC	None	None	92,000	87%	13%	--	--	--	--	--
		Mortar	Asphalt	94,000	38%	17%	0.01%	45%	--	--	--
	DI	Mortar	PE Tube	60,000	60%	27%	0.01%	--	--	13%	--
	Concrete	Mortar	None	81,000	99%	0.5%	0.1%	--	--	--	--
		Mortar	Epoxy	33,000	83%	--	0.1%	--	17%	--	--
		Mortar	PE Tube	35,000	78%	--	0.1%	--	--	22%	--
	Steel	Mortar	Tape	35,000	79%	--	0.1%	--	--	--	21%
36	PVC	None	None	150,000	86%	14%	--	--	--	--	--
		Mortar	Asphalt	160,000	43%	18%	0.01%	39%	--	--	--
	DI	Mortar	PE Tube	110,000	61%	26%	0.01%	--	--	13%	--
	Concrete	Mortar	None	100,000	99%	0.6%	0.1%	--	--	--	--
		Mortar	Epoxy	49,000	83%	--	0.1%	--	17%	--	--
		Mortar	PE Tube	56,000	73%	--	0.1%	--	--	27%	--
	Steel	Mortar	Tape	52,000	78%	--	0.1%	--	--	--	22%

Figure 8: Energy Use Results for 100 feet of Pipe

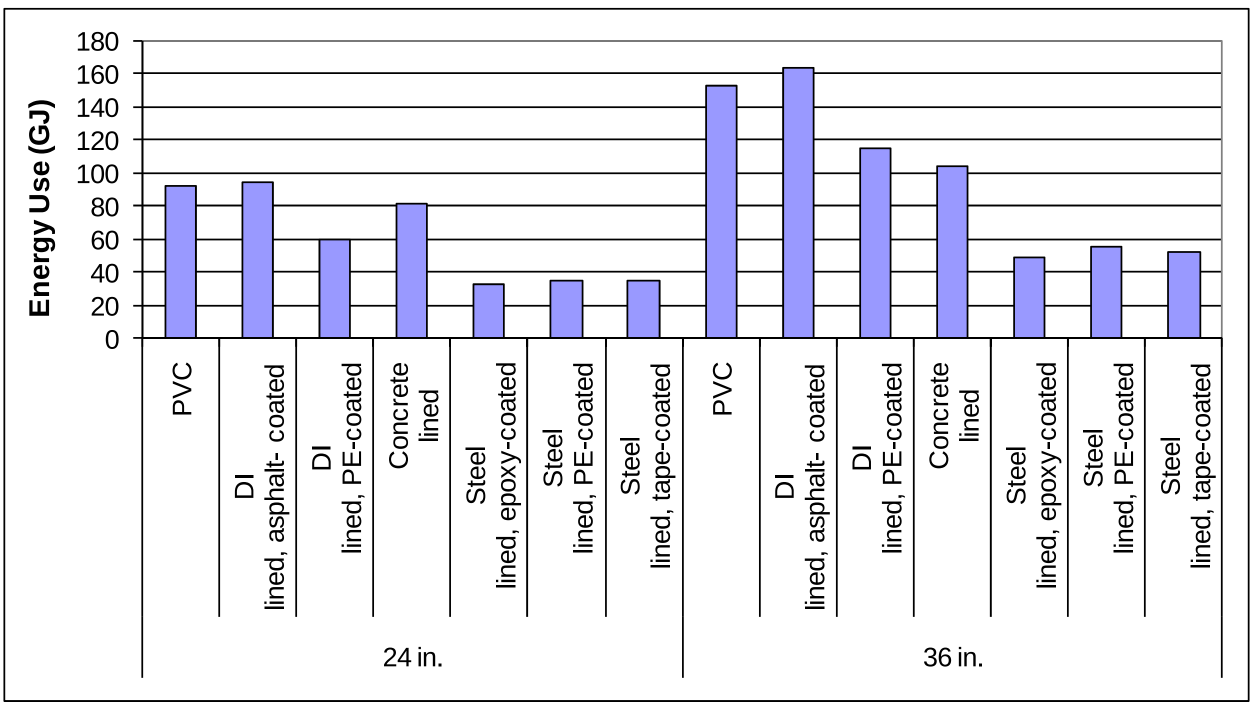


Table 11 shows that for all pipe types, except when asphalt coating is used, pipe manufacturing creates the majority of the effects. Asphalt coating is the most environmentally intensive; the coating itself produces 39 percent of the effects for the 24-inch pipe and 45 percent of the 36-inch pipe. This asphalt coating analysis is for only one coat; multiple coats, up to three, are sometimes used and will have even higher results.

Pipe gasket production for concrete pipe consumes less than 1 percent of the energy for 100 feet of pipe. For PVC and DI pipe, gaskets consume 13 percent to 27 percent of the energy. It was assumed that steel pipe does not use gaskets. Coatings, besides asphalt, consume energy in the same proportion, 13 percent to 27 percent.

The results indicate that steel pipe is environmentally-preferable over other alternatives. Epoxy is the best alternative for coatings. However, it should be noted that the EIO-LCA sector for steel pipe is for “Metal pipe, valves, and fittings,” the same sector as for DI pipe. However, steel pipe is less expensive than DI pipe and therefore, based on the current methodology, consumes less energy and creates fewer emissions. At both 24-inch and 36-inch diameters, epoxy-coated steel pipe is the most preferable alternative.

The analysis does not account for differences in the rate of breaks, increased roughness (friction) over time and therefore energy for pumping and other maintenance-related differences between materials. The necessary data were not available for all pipe materials so that a fair comparison could be made. Because different pipe materials have been used at different points in history (i.e., cast iron is generally nearing the end of its service life, plastic pipe has been used in recent decades), the maintenance information for different materials varies widely.

4.2.2 Tank Analysis Outcomes

Assumptions in the analysis are summarized in Appendix E.4. Figure 9 shows a typical summary results page. The results are for the input in Figure 6. By clicking on the “View All Results” box, the user also can see the individual results for production of tank foundations, energy consumption, and pipe production.

Figure 9: Tank Analysis Results Worksheet

VIEW ALL RESULTS | VIEW SUMMARY

General	Total Tank Production							Tank (No foundations)						
Material	Energy (TJ)	GHG (Mg)	CO (Mg)	NO_2 (Mg)	PM10 (Mg)	SO_2 (Mg)	VOC (Mg)	Energy (TJ)	GHG (Mg)	CO (Mg)	NO_2 (Mg)	PM10 (Mg)	SO_2 (Mg)	VOC (Mg)
Concrete tank	10.2	732	4.9	3.2	0.7	3.4	0.5	6.7	481	3.2	2.1	0.5	2.2	0.3
Steel tank, ground-level	5.0	378	2.9	1.3	0.3	1.4	2.3	1.5	127	1.2	0.2	0.1	0.3	2.2
Steel tank, elevated	4.1	340	3.2	0.7	0.3	0.8	5.6	3.9	326	3.1	0.6	0.2	0.7	5.6
Wood tank	9.8	696	5.8	3.8	1.3	2.6	1.1	5.6	393	3.8	2.5	1.0	1.2	1.0

To demonstrate the capabilities of WESTLite, hypothetical tank configurations were compared. The parameters of the four scenarios considered are outlined in Table 12.

Table 12: Tank Scenario Summary

	Tank Height (ft)	Foundation Thickness (ft)	Tank Configuration	Additional Annual Electricity Use (kWh)	Additional Piping Requirements (ft)
Scenario One: 0.5 MG tank capacity					
Concrete	10	2	AHGL	--	4000
Steel, ground-level	8	1.5	BHGL	1430	--
Steel, elevated	--	2	AHGL	--	500
Wood	7	1.5	BHGL	1430	
Scenario Two: 1 MG tank capacity					
Concrete	15	2.5	AHGL	--	8000
Steel, ground-level	12	2	BHGL	4126	--
Steel, elevated	--	2	AHGL	--	1500
Wood	10	2	BHGL	4126	1000
Scenario Three: 5 MG tank capacity					
Concrete	30	4	AHGL	--	10000
Steel, ground-level	50	6	BHGL	8595	--
Scenario Four: 10 MG tank capacity					
Concrete	50	7	AHGL	--	10000
Steel, ground-level	100	10	AHGL	--	3000
Notes:	AHGL = Above hydraulic grade line				
	BHGL = Below hydraulic grade line				

The general guidelines used in the analysis follow. Tanks designed to be at the hydraulic grade line must be placed at higher elevations at a distance from the remainder of the system; additional pipe was analyzed to account for this. Since siting larger tanks is more difficult, the amount of pipe increased with the size of the tank. Tanks designed below the hydraulic grade line must pump water back into the system and electricity use is assigned to those tanks. Valves and controls for the tanks are similar and therefore were excluded from the analysis. Emission factors for these four scenarios are included in Table 13. Results are reported in terajoules (TJ) for energy and Mg for air emissions. Table 14 provides results for the energy use contribution of each component to the final results. Figure 10 shows the results for constructing 10 MG of storage using each size tank (i.e., ten 1-MG tanks will be installed).

Table 13: Tank Scenario Emission Factors

Material	Scenario One: 0.5 MG			Scenario Two: 1 MG			Scenario Three: 5 MG			Scenario Four: 10 MG		
	Energy (TJ)	GHG (Mg)	SO_x (Mg)	Energy (TJ)	GHG (Mg)	SO_x (Mg)	Energy (TJ)	GHG (Mg)	SO_x (Mg)	Energy (TJ)	GHG (Mg)	SO_x (Mg)
Concrete	7.3	520	2.4	11	770	3.6	32	2300	11	62	4500	21
Steel, ground-level	3.3	250	0.8	6.1	470	1.5	20	1500	5.2	32	2400	9.1
Steel, elevated	2.7	220	0.5	4.2	350	0.8	--	--	--	--	--	--
Wood	5.4	390	1.4	11	790	2.6	--	--	--	--	--	--
Note:	TJ = Terajoule											

Table 14: Tank Scenario Component Energy Results

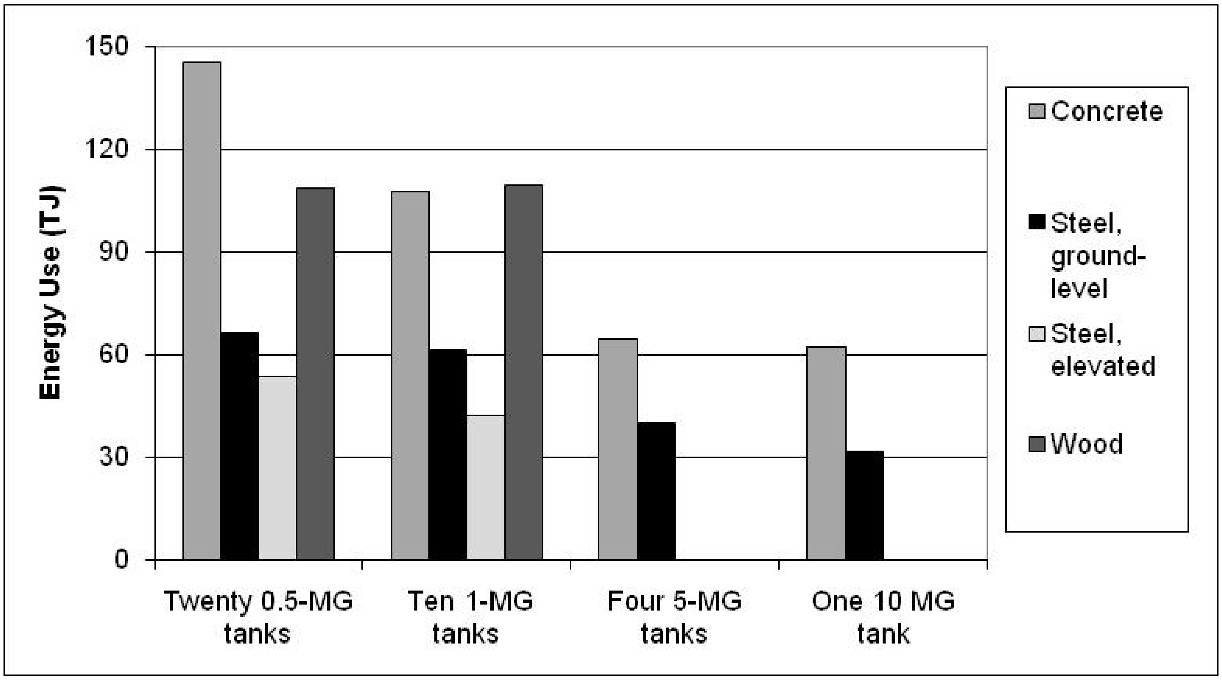
Material	Scenario One: 0.5 MG			Scenario Two: 1 MG			Scenario Three: 5 MG			Scenario Four: 10 MG		
	Tank	Found-ation	Energy or Pipe	Tank	Found-ation	Energy or Pipe	Tank	Found-ation	Energy or Pipe	Tank	Found-ation	Energy or Pipe
Concrete	67%	29%	4.1%	62%	32%	5.5%	54%	43%	2.3%	52%	47%	1.2%
Steel, ground-level	29%	59%	12%	25%	57%	18%	26%	63%	12%	34%	66%	0.69%
Steel, elevated	91%	7.3%	1.4%	93%	4.7%	2.6%	--	--	--	--	--	--
Wood	51%	42%	7.1%	51%	38%	11%	--	--	--	--	--	--

Table 13 shows that steel tanks are the environmentally preferable option for the scenarios considered. Elevated tanks are the most preferred if the volume is less than 1 MG. Concrete tanks consume the most energy, with the exception of the wood tank in Scenario Two. This indicates that wood tanks are more competitive at volumes smaller than 1 MG. Steel tanks consume less, between 36 percent and 62 percent, of the energy of concrete tanks for the four scenarios.

Manufacturing the tank itself consumes the majority of emissions for all tank types except ground-level steel tanks. The foundations for the steel tanks were more massive and therefore consumed more energy than for other types of tanks. When additional piping was needed to connect the tank to the existing distribution system, the contribution to energy consumption was less than 5 percent. When additional electricity was required, the contributions were more significant and ranged from 7 percent to 18 percent of the total energy consumption.

Figure 10 shows there are economies of scale to water storage for four scenarios. All scenarios compare a total of 10 MG of storage volume with either one large tank or multiple smaller ones. With the exception of a small increase in energy use associated with wood tanks for larger tanks, the trend is that larger tanks use less energy for equivalent volumes of storage.

Figure 10: Results Summary for 10 MG of Storage



4.3 Task 4 Conclusions and Recommendations

The Task 4 analysis was intended to provide a means for utilities to analyze small-scale design decisions related to piping and tank choices. The new tool created in Task 4, WESTLite, provides a straight-forward means to conduct these assessments.

The pipe analysis determined that steel pipe is generally environmentally preferable to other materials for the assumptions in this analysis. If coatings are used, epoxy is preferred. However, the EFs used in the analysis for pipe applies to all metal pipe and is the same as the EF applied to DI and cast iron (CI) pipe. To obtain more precise results, a specific EF for steel should be used.

The sample scenarios analyzed indicate that using steel tanks is consistently preferable to constructing concrete tanks. However, some assumptions may not be consistent with the designs used in all cases. Additional analyses are needed to determine where the breakeven points are for steel and concrete tanks.

CHAPTER 5:
Task 5 – Include Life-Cycle Effects of Electricity Generation

The existing WEST was improved to include the life-cycle environmental effects of electricity generation and additional detail about impacts of sludge disposal.

5.1 Task 5 Approach

The researchers revised WEST to include EFs for electricity generation that capture cradle-to-grave effects. The user can now use either direct or life-cycle EFs in the analysis. A new activity was created for sludge disposal and added the necessary data entry, calculation, results, and explanatory worksheets. This activity includes EFs incorporating the long-term effects of sludge disposal in a landfill or by incineration. A description of the task, documentation of changes associated with this task, and results from repeated analysis of the case studies analyzed as part of the Phase One work are included in this chapter.

5.1.1 Life-cycle Electricity Approach

The Phase One version of WEST calculated emissions from electricity production using data from the U.S. EPA's EGRID database (Year 2000 data; USEPA 2004). The EGRID database reports smoke-stack, or direct, emissions. It does not provide a comprehensive view of the environmental effects of electricity generation because it excludes life-cycle effects, such as mining coal, acquiring natural gas, and manufacturing materials used to construct power plants and infrastructure. EGRID also assumes that no emissions are associated with most renewable energy sources (e.g., geothermal and wind power). However, these energy sources will have emissions associated with their life-cycle emissions, for example, from obtaining raw materials, manufacturing equipment, and decommissioning. Similarly, indirect emissions will increase the environmental effects attributed to other energy sources such as coal and natural gas.

As a part of Task 5 activities, WEST was updated to include EFs that incorporate the entire life cycle. A comprehensive literature review was completed to determine a reasonable range of life-cycle EFs both nationally and internationally and included: (Corti and Lombardi 2004; Cuddihy et al 2005; Gagnon et al 2002; Heller et al 2004; Kannan et al 2007; Koch 2001; Lee et al 2004; Lenzen and Munksgaard 2002; Meier 2002; May and Brennen 2003; Pacca and Horvath 2002; Pehnt 2006; Rashad and Hammad 2000; Riva et al 2006; Schleisner 2000; Spath and Mann 1997; Spath et al 1999; Spath and Mann 2000; University of Sydney 2006; and Wilson 1990). Additionally, WEST was revised to include Year 2004 EGRID data.

The EFs from these studies are included in the background material section of WEST ("Elect EFs" sheet). Factors were found for the following parameters: energy use, greenhouse gases (GHG, in units of CO_2(e)), NO_x, SO_x, PM, and VOCs (sometimes referred to as non-methane VOCs [NMVOCs] and hydrocarbons [HC]). Final EFs for each of the eight electricity sources included in WEST are presented in Table 15, including both the revised direct and life-cycle values specific to California.

Table 15: Life-cycle Emission Factors by Generation Type for California

Source	Coal	Oil	Natural Gas	Nuclear	Other Fossil Fuel	Hydro	Bio-mass	Wind	Solar	Geo-thermal
Direct Emission Factors (Units: g.kWh except energy, MJ/kWh)										
Energy	3.6	3.6	3.6	3.6	3.6	0	3.6	0	0	0
GHG	1020	912	555	0	398	0	32	0	0	0
NO_x	0.34	0.69	0.20	0	1.1	0	1.1	0	0	0
SO_x	1.36	3.51	0.01	0	0.016	0	0.10	0	0	0
VOC	0	0	0	0	0	0	0	0	0	0
PM		0	0	0	0	0	0	0	0	0
CO	0.24	0.24	0.24	0	0.24	0	0.00	0	0	0
Life-cycle Emission Factors (Units: g.kWh except energy, MJ/kWh)										
Energy	10[1]	9[2]	8.6[1]	11[1]	9[1]	0.29[2]	0.43[1]	0.29[2]	0.64[1]	0.59[1]
GHG	1059[3]	957[4]	696[3]	17[1]	417[5]	55[1]	56[3]	31[1]	64[1]	28[1]
NO_x	0.37[3]	0.92[4]	0.36[3]	0.065[1]	1.2[5]	0.019[1]	1.4[3]	0.019[1]	6.5[1]	0.19[1]
SO_x	1.4[3]	4.6[4]	2.0[3]	0.022[1]	0.016[5]	0.004[1]	0.11[3]	0.043[1]	0.18[1]	0.062[1]
VOC	3.2[1]	0.13[2]	0.069[1]	0.0045[1]	NA	0.004[1]	0.15[1]	0.012[1]	0.09[1]	0.035[1]
PM	0.016[1]	0.022[1]	0.37[1]	NA	NA	0.0057[2]	0.34[1]	0.0095[2]	0.07[1]	NA
CO	0.12[1]	0.24[6]	0.55[2]	NA	0.24[6]	0.067[2]	0.083[1]	0.097[2]	0.11[2]	0.21[1]

Notes:

[1] These values were determined based on average values for US plants found in the literature review.

[2] These values are average values from the literature because no US data was available.

[3] These values are average direct emissions from California plants using the appropriate fuel source (USEPA 2007). Life-cycle, emissions were estimated using data from NREL reports (Spath et al. 1997, 1999, 2000).

[4] Values determined based on a nationwide average of values for direct emissions from oil plants in California (USEPA 2007). Life-cycle emissions were estimated using an international source (Lee 04). U.S. data was unavailable.

[5] These values were determined based on a average values for direct emissions from California plants using other fossil fuels (USEPA 2007). Life-cycle emissions estimates use averages from coal and natural gas plants.

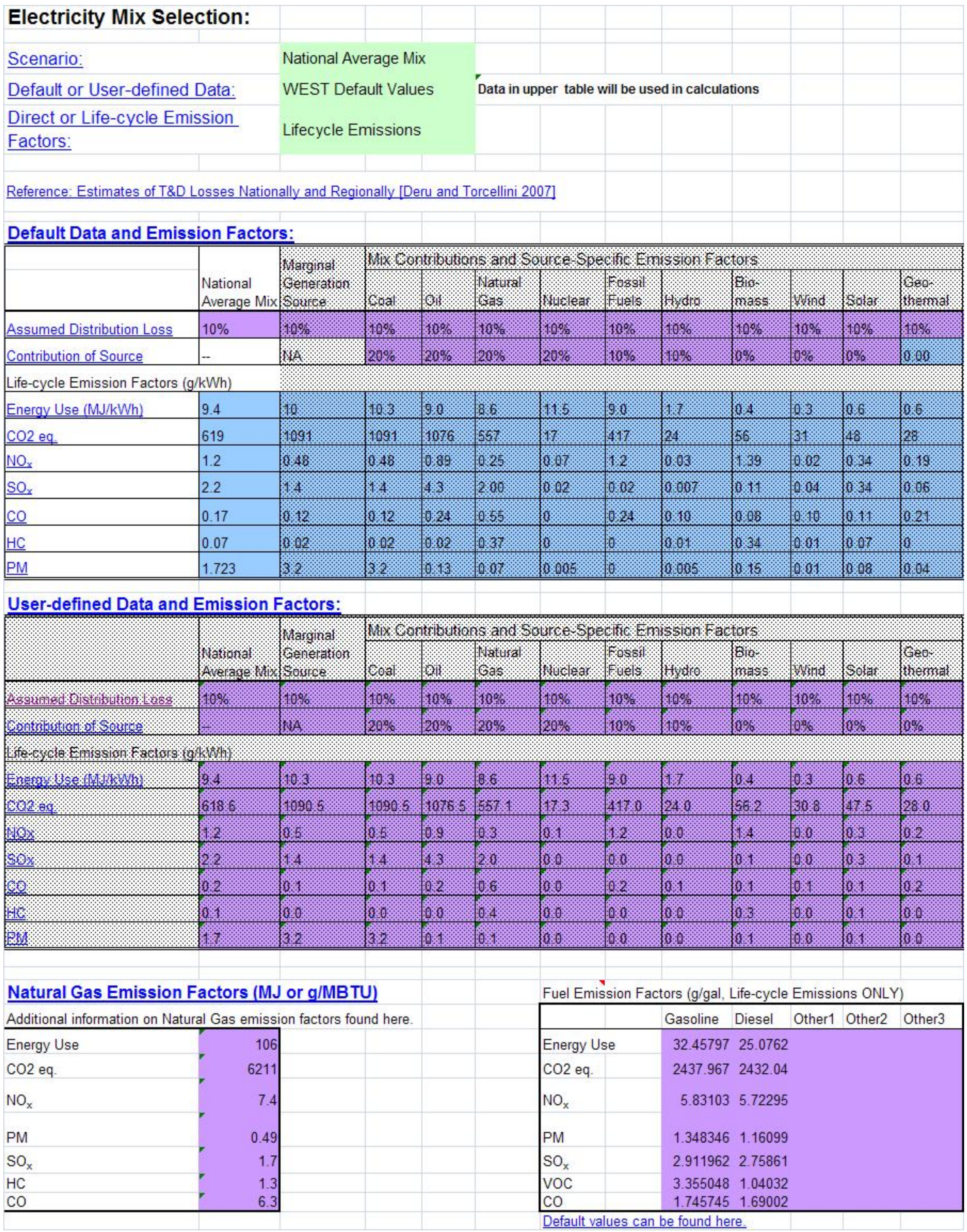
[6] No estimates of life-cycle emissions were found. An estimate of direct emissions is included.

NA = Not available, assumed to be zero

WEST also contains direct and life-cycle EFs for each of the 50 states and for the United States national average mix. To determine state average EFs for combustion-based electricity sources, the EGRID EFs for the appropriate source for each state were multiplied by estimates of the proportion of non-generation emissions associated with that source found in reports from the National Renewable Energy Laboratory (NREL) (Spath and Mann 1997, Spath et al. 1999, Spath and Mann 2000). For other sources, the life-cycle EF was determined based on a literature review and calculated for all states. Details are provided in Table 15.

The EF for each source was multiplied by its contribution to each state's resource mix. Figure 11 shows the worksheet where energy mix alternatives and EFs can be edited by the user for custom energy analysis. The default distribution loss of 10 percent represents the national average loss; the average for the Western grid is 8.4 percent (Deru and Torcellini 2007). In addition, the user can access a table of EF ranges for specific electricity generation technologies (Table 16) and international areas (Table 17) to use as guidelines for establishing custom EFs.

Figure 11: Energy Mix Data Entry Page



Electricity Mix Selection:

Scenario:	National Average Mix
Default or User-defined Data:	WEST Default Values
Direct or Life-cycle Emission Factors:	Lifecycle Emissions

Data in upper table will be used in calculations

Reference: Estimates of T&D Losses Nationally and Regionally [Deru and Torcellini 2007]

Default Data and Emission Factors:

	National Average Mix	Marginal Generation Source	Mix Contributions and Source-Specific Emission Factors									
			Coal	Oil	Natural Gas	Nuclear	Fossil Fuels	Hydro	Bio-mass	Wind	Solar	Geo-thermal
Assumed Distribution Loss	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Contribution of Source	--	NA	20%	20%	20%	20%	10%	10%	0%	0%	0%	0.00
Life-cycle Emission Factors (g/kWh)												
Energy Use (MJ/kWh)	9.4	10	10.3	9.0	8.6	11.5	9.0	1.7	0.4	0.3	0.6	0.6
CO2 eq.	619	1091	1091	1076	557	17	417	24	56	31	48	28
NO_x	1.2	0.48	0.48	0.89	0.25	0.07	1.2	0.03	1.39	0.02	0.34	0.19
SO_x	2.2	1.4	1.4	4.3	2.00	0.02	0.02	0.007	0.11	0.04	0.34	0.06
CO	0.17	0.12	0.12	0.24	0.55	0	0.24	0.10	0.08	0.10	0.11	0.21
HC	0.07	0.02	0.02	0.02	0.37	0	0	0.01	0.34	0.01	0.07	0
PM	1.723	3.2	3.2	0.13	0.07	0.005	0	0.005	0.15	0.01	0.08	0.04

User-defined Data and Emission Factors:

	National Average Mix	Marginal Generation Source	Mix Contributions and Source-Specific Emission Factors									
			Coal	Oil	Natural Gas	Nuclear	Fossil Fuels	Hydro	Bio-mass	Wind	Solar	Geo-thermal
Assumed Distribution Loss	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Contribution of Source	--	NA	20%	20%	20%	20%	10%	10%	0%	0%	0%	0%
Life-cycle Emission Factors (g/kWh)												
Energy Use (MJ/kWh)	9.4	10.3	10.3	9.0	8.6	11.5	9.0	1.7	0.4	0.3	0.6	0.6
CO2 eq.	618.6	1090.5	1090.5	1076.5	557.1	17.3	417.0	24.0	56.2	30.8	47.5	28.0
NOx	1.2	0.5	0.5	0.9	0.3	0.1	1.2	0.0	1.4	0.0	0.3	0.2
SOx	2.2	1.4	1.4	4.3	2.0	0.0	0.0	0.0	0.1	0.0	0.3	0.1
CO	0.2	0.1	0.1	0.2	0.6	0.0	0.2	0.1	0.1	0.1	0.1	0.2
HC	0.1	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.3	0.0	0.1	0.0
PM	1.7	3.2	3.2	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0

Natural Gas Emission Factors (MJ or g/MBTU)

Additional information on Natural Gas emission factors found here.

Energy Use	106
CO2 eq.	6211
NO_x	7.4
PM	0.49
SO_x	1.7
HC	1.3
CO	6.3

Fuel Emission Factors (g/gal, Life-cycle Emissions ONLY)

	Gasoline	Diesel	Other1	Other2	Other3
Energy Use	32.45797	25.0762			
CO2 eq.	2437.967	2432.04			
NO_x	5.83103	5.72295			
PM	1.348346	1.16099			
SO_x	2.911962	2.75861			
VOC	3.355048	1.04032			
CO	1.745745	1.69002			

Default values can be found here.

Table 16: Emission Factors per kilowatt-hour by Generation Technology

Technology	Energy (MJ)		GHG (g)		NO_x (g)		PM (g)		SO_x (g)		VOC (g)		CO (g)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Coal	12	13	607	1506	0.19	5.3	0.022	9.2	0.026	32	0.19	5.3	0.096	0.49
Modern plant w/sulphur scrub	--	--	960	--	0.50	5.3	0.030	0.66	0.10	--	0.018	0.029	--	--
IGCC with decarbonization	--	--	359	--	--	--	--	--	--	--	--	--	--	--
Oil	11	--	459	900	1.3	2.3	0.13	--	2.3	8.0	0.022	0.022	--	--
Natural Gas	7.8	8.4	311	1590	1.3	2.3	0.0010	1.1	2.3	8.0	0.022	--	0.17	0.94
Simple	--	--	334	1230	--	--	--	--	--	--	--	--	--	--
Combined cycle	7.8	8.4	311	655	0.013	1.8	0.0010	0.010	0.0040	15	0.072	0.16	0	0
Nuclear														
Light water	--	--	2.8	130	--	--	--	--	--	--	--	--	--	--
Heavy water	--	--	0.20	120	--	--	--	--	--	--	--	--	--	--
Hydro														
Reservoir	0.10	0.10	5.0	50	0	0.050	0.0050	0.026	0.0070	0.017	0.0060	0.0060	0.059	0.059
Run of River	0.14	0.14	0	44	0	0.049	0.0010	0.031	0.0010	0.028	0.011	0.011	0.074	0.074
Biomass														
Biogas	0.009	--	-580	--	0.58	--	0.038	--	0.368	--	0.17	--	0.72	--
Forestry wood	0.18	0.53	27	86	0.26	1.4	0.060	0.13	0.026	0.94	0.027	0.16	0.19	0.90
Waste wood	0.36	0.36	15	101	0.70	2.0	0.109	0.32	0.012	0.315	0	0.12	0.41	0.41
IBGCC with decarbonization	--	--	-594	--	--	--	--	--	--	--	--	--	--	--
Solar														
PV park	0	0	21	279	0.30	0.38	0.06	0.08	0.3	0.38	0	0	0	0
Distributed PV	0.63	2.9	39	217	0.34	0.34	0.12	0.12	0.288	0.288	0.020	0.020	0.14	0.14
Solar thermal	0.14	--	14	--	0.073	--	0.04	--	0.047	--	0.0021	--	0.09	--
Wind														
Onshore	0.12	--	9.7	--	0.030	--	0.011	--	0.02	--	0.0024	--	--	--
Offshore	0.11	--	9	--	0.050	--	--	--	0.03	--	--	--	--	--

Notes: IGCC = Integrated gasification combined cycle
IBGCC = Integrated biomass gasification combined cycle

Sources: Corti and Lombardi 2004; Cuddihy et al 2005; Gagnon et al 2002; Heller et al 2004; Kannan et al 2007; Koch 2001; Lee et al 2004; Lenzen and Munksgaard 2002; Meier 2002; May and Brennen 2003; Pacca and Horvath 2002; Pehnt 2006; Rashad and Hammad 2000; Riva et al 2006; Schleisner 2000; Spath et al 1997; Spath et al 1999; Spath and Mann 2000; University of Sydney 2006; Wilson 1990

Table 17: Emission Factors per kilowatt-hour by Geographic Location

Technology/ Location	Energy (MJ)		GHG (g)		NO_x (g)		PM (g)		SO_x (g)		VOC (g)		CO (g)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Coal														
Korea	--	--	1001	1155	2.0	2.5	0.22	0.31	0.78	3.5	--	--	--	--
Japan	--	--	990	--	--	--	--	--	--	--	--	--	--	--
EU	--	--	790	1182	0.70	5.3	0.030	0.66	0.70	32	0.018	0.029	--	--
Australia	--	--	681	1506	0.19	3.4	0.022	0.55	0.026	4.2	0.011	0.67	0.096	0.49
Oil														
Japan	--	--	742	--	--	--	--	--	--	--	--	--	--	--
Singapore	11	--	854	--	--	--	--	--	--	--	--	--	--	--
Korea	--	--	847	--	2.3	--	0.13	--	3.3	--	--	--	--	--
EU		--	540	900	--	1.3	--	--	--	2.3	--	--	--	--
Natural Gas														
EU		--	311	734	0.01	1.5	--	--	0.0040	15	0.072	1.5	--	--
Australia		--	404	1590	0.2	3.8	--	--	0.032	4.6	0.012	3.8	--	--
Korea		--	512	--	2.5	--	0.056	--	0.963	--	--	--	--	--
Singapore	7.8	--	473	--	--	--	--	--	--	--	--	--	--	--
Nuclear														
Australia		--	10	130	--	--	--	--	--	--	--	--	--	--
Koren		--	0.20	2.77	0.006	0.017	0.016	0.022	0.018	--	--	--	--	--
Japan		--	21	44	--	--	--	--	--	--	--	--	--	--
Hydro														
EU	0.10	0.14	2.0	72	0.003	0.049	0.026	5	0.005	0.06	0	0.011	0.059	0.074
Australia	--	--	6.5	44	--	--	--	--	--	--	--	--	--	--
Korea	--	--	25	--	0.031	--	0.047	--	0.47	--	--	--	--	--
Japan	--	--	18	--	--	--	--	--	--	--	--	--	--	--
Biomass														
EU	0.01	0.53	-594	101	0.258	1.95	0.038	0.32	0.012	0.37	0	0.17	0.19	0.90
Solar														
EU	0.14	1.5	13	731	0.016	0.34	0.012	0.19	0.024	0.49	0.0021	0.070	0.085	0.14
Australia	--	--	53	217	--	--	--	--	--	--	--	--	--	--
Singapore	2.9	--	217	--	--	--	--	--	--	--	--	--	--	--
Japan	--	--	59	--	--	--	--	--	--	--	--	--	--	--
Wind														
EU	0.11	0.12	7.0	124	0.014	0.05	0.005	0.035	0.02	0.087	0	0.0024	0	0
Australia	--	--	13	40	--	--	--	--	--	--	--	--	--	--

Sources: Corti and Lombardi 2004; Cuddihy et al 2005; Gagnon et al 2002; Heller et al 2004; Kannan et al 2007; Koch 2001; Lee et al 2004; Lenzen and Munksgaard 2002; Meier 2002; May and Brennen 2003; Pacca and Horvath 2002; Pehnt 2006; Rashad and Hammad 2000; Riva et al 2006; Schleisner 2000; Spath et al 1997; Spath et al 1999; Spath and Mann 2000; University of Sydney 2006; Wilson 1990

5.1.2 Sludge Disposal

In addition to the existing activities, material production, material delivery, equipment use, and energy production, a sludge disposal activity was added to WEST. This activity includes equipment use associated with handling sludge, sludge transfer to the disposal site, and the effects of long-term disposal.

Prior research on sludge disposal has primarily considered sludge from WWTPs. Wastewater sludge contains significant organic matter which potentially can be used in a variety of ways, including land application and as filler for cement. Because the nutrient and heating value of water treatment sludge is uncertain and is significantly lower in volume than wastewater sludge, many of these applications have not been researched for water treatment sludge. As a result, the only disposal alternatives included in WEST are landfilling and incineration.

In addition, most research on general waste disposal involves municipal solid waste (MSW). Sludge is specifically excluded from MSW. However, because more appropriate data were unavailable, EFs for WEST were obtained from two sources specific to MSW (USEPA 2006; Denison 1996). Waste collection effects were excluded from both sources. In contrast to MSW, sludge is assumed to be delivered infrequently by a dedicated truck rather than as part of community collection process. The collection effects will be estimated using the actual distance between the plant and disposal site provided by the user and EFs appropriate for the transport vehicle. The long-term disposal EFs in WEST are shown in Table 18.

Table 18: Sludge Disposal Emission Factors

Disposal Method			Efficiency	Energy (MJ/ton)	GHG (Mg/ton)	NOx (g/ton)	PM (g/ton)	SOx (g/ton)	VOC (kg/ton)	CO (g/ton)
Incineration				-5300	-0.12	-360	-950	-2600	-990	110
Landfill	National average[2]			240	0.42	200	45	29	0	190
	No gas recovery			--	1.6	--	--	--	--	--
	Recovered gas flared		60%	--	0.44	--	--	--	--	--
			75%	--	0.15	--	--	--	--	--
			85%	--	-0.043	--	--	--	--	--
			95%	--	-0.23	--	--	--	--	--
	Recovered gas for electricity		60%	--	0.25	--	--	--	--	--
			75%	--	-0.08	--	--	--	--	--
			85%	--	-0.3	--	--	--	--	--
			95%	--	-0.52	--	--	--	--	--

Notes:

[1] GHG EFs are from EPA's Waste Reduction Model (WARM; USEPA 2006). Other EFs are from (Dennison 1996).

[2] Default value.

The nature of water treatment sludge is not well documented and is dependent on the source of the water. The sludge will contain chemicals, particularly coagulants (e.g., alum, ferric chloride). Other components may be inorganic or organic particles; the proportion of each may vary depending on the water source. Emission factors for three MSW materials are available in WEST to reflect potential mixes of sludge materials: glass, yard trimmings, and MSW. These three examples are included because the EFs are available (USEPA 2006). Glass EFs are indicative of primarily inorganic sludge; yard trimmings EFs reflect highly organic sludge; and MSW, a mix of organic and inorganic materials. The user may select the most appropriate material or, using these values as guidance, may specify a custom EF associated with a landfill. The default values shown in Table 18 are appropriate for general MSW.

5.1.3 Case Studies

To demonstrate the updated capabilities of WEST, two case studies originally analyzed in the Phase One work were reanalyzed. One Southern California utility is located in northern San Diego County. The Northern California utility is located in the San Francisco Bay Area. The details of these case studies have been previously reported (Horvath 2005; Stokes and Horvath 2006). A brief description of the two systems follows.

The Southern California utility (SC) obtains 92 percent of its water supply from imported sources, a combination of water from the CRA and the SWP. Approximately 8 percent of their water is obtained by desalinating saline groundwater; less than 1 percent of the SC's water is recycled wastewater.

The Northern California utility (NC-Current) obtains 72 percent of their water from local surface water (reservoirs) and 2 percent from recycling wastewater. The remaining 26 percent is currently supplied by importing water from a neighboring county. The utility has proposed replacing the imported water with desalinated water from the San Francisco Bay. The proposed supply mix which includes desalination will be referred to as NC-Proposed.

5.2 Task 5 Outcomes

Table 19 summarizes the emissions per functional unit of water produced (100 AF) for each water source in the systems. In addition, it provides the overall EF for the SC and NC-Current utilities, as well as the NC-Proposed system which replaces imported with desalinated water.

Table 19: Emissions per functional unit for each source and system

Results per 100 AF		Energy (MJ)		GHG (Mg)		NO_x (kg)		PM (kg)		SO_x (kg)		VOC (kg)		CO (kg)	
		SC	NC	SC	NC	SC	NC	SC	NC	SC	NC	SC	NC	SC	NC
Source	Imported	1700	1700	100	100	100	140	25	32	300	320	54	59	300	350
Source	Desalinated	2500	5000	150	330	150	350	37	87	440	990	86	180	440	1000
Source	Recycled	1600	2100	93	130	81	120	21	31	270	360	48	68	270	360
Source	Local Surface	--	930	--	59	--	120	--	27	--	200	--	41	--	240
System	Current	1800	1100	110	71	106	120	25	32	310	320	57	46	310	270
System	Proposed	--	2000	--	130	--	180	--	42	--	410	--	76	--	450

Note: These results were refined as part of future tasks, The values are qualitatively valuable but should not be considered final. For final results, see Chapter 12.

The results indicated that the effects of desalinated water are significantly larger than the effects of the other sources, especially for the NC-Proposed's more saline water source. The local surface water in the NC-Current system is the environmentally preferable choice for many emissions, except NO_x, PM, and VOCs. The emissions of these chemicals are comparable to imported and recycled water. Unfortunately, this water source is not available in much of California. Imported and recycled water produce comparable effects for most chemicals. From a system-wide perspective considering energy and GHG, the NC-Current is preferable.

Figure 12 provides further information by comparing the NC-Current, and NC-Proposed results relative to the SC system results (i.e., the SC results are 100 percent). The figure shows that energy use and GHG emissions in the imported water systems are similar. However, the NC system creates more environmental effects for other emissions from the imported system, as well as emissions from desalinated and recycled water. On the other hand, the NC-Current system which includes significant local surface water supply is preferable to the SC system for all effects except NO_x, SO_x, and PM.

Figure 12: Comparison of SC and NC Results

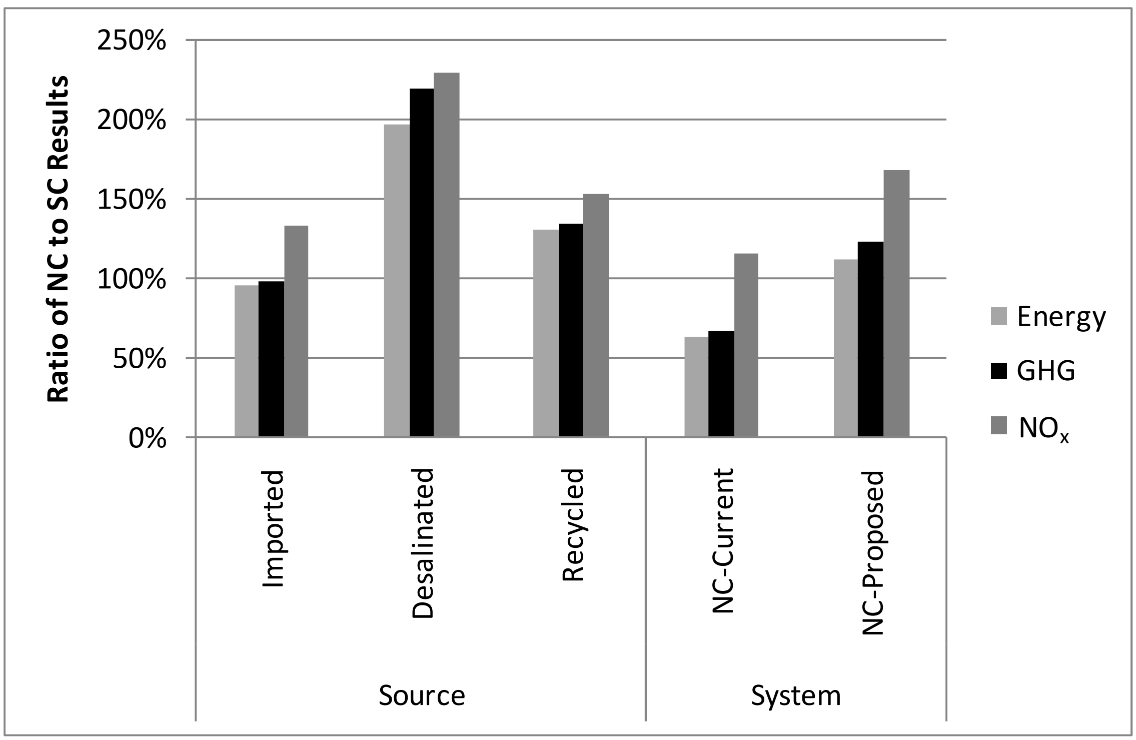


Figure 13 shows breakdown of results by activity for GHG and NO_x for each source from the case studies. GHG and NO_x were selected as generally representative of other emissions. Figure 13 shows that energy production is the most significant source of emissions for all sources, except NO_x from the NC-Current's local and imported water. Energy production ranges from 23 to 97 percent of the total results. Material production is generally the next most important activity: 3 to 68 percent of the total results. Material production is most significant for

NO_x emissions from the NC-Current's local surface water source (68 percent) and the imported water system (48 percent) because of the amount of infrastructure required to supply water. Energy production for the imported water system is a similar 47 percent. Material delivery, equipment use, and sludge disposal are less than 7 percent of the total results for all scenarios.

Figure 13: Activity Contribution to GHG and NO_x Results

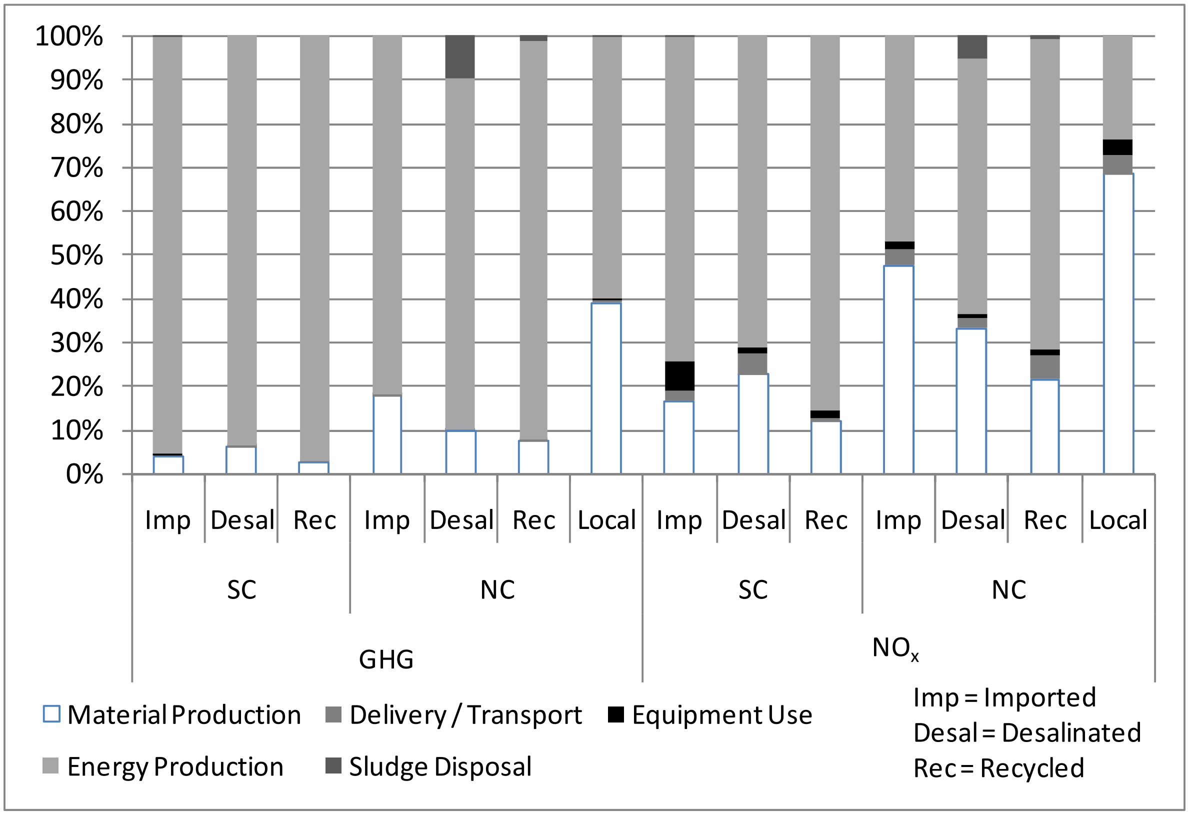


Figure 14 illustrates the contribution of life-cycle phases (construction, operation, maintenance, and end-of-life [EOL]). Figure 15 shows the contribution of water supply phases (supply, treatment, and distribution) to the overall system results (i.e., per 100 AF of water provided by the utility). The results for each source are proportioned according to the contribution to the overall supply.

For life-cycle phases, operation dominates the results primarily because day-to-day electricity and chemical use occurs during this phase. Maintenance is also significant for the NC-Current system because their distribution system is extensive and complex. End of life is least significant; for all but the NC-Current system, the EOL contribution is less than 0.5 percent of the results for all chemicals.

Figure 14: Life-cycle Phase Results for Utilities

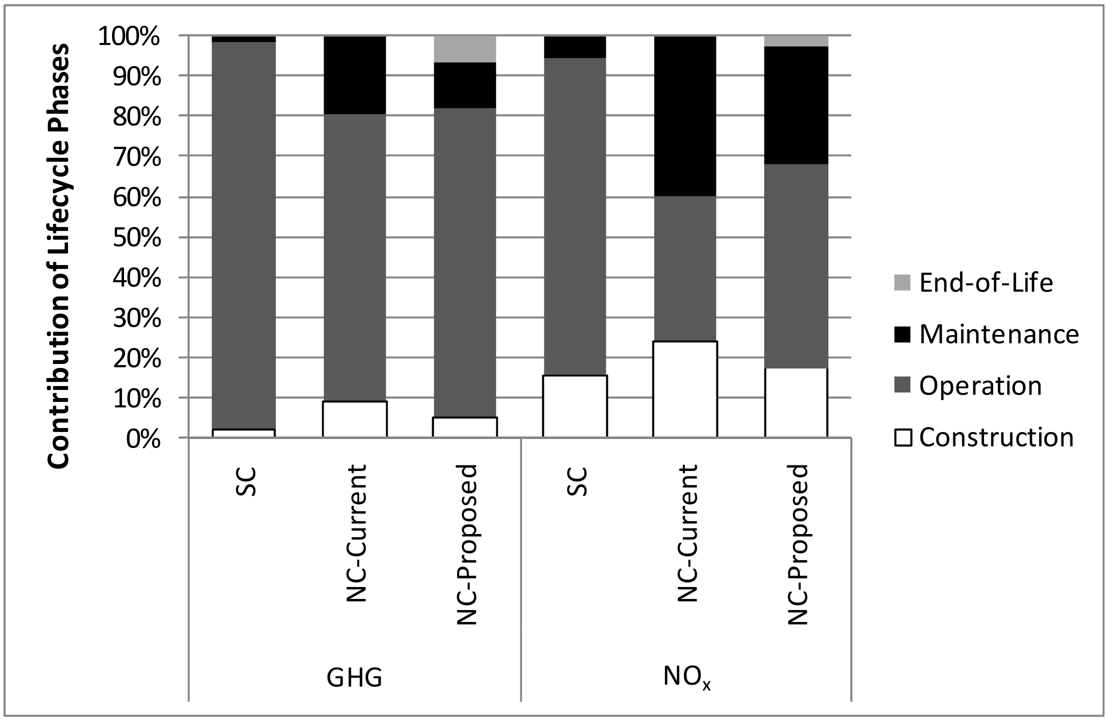
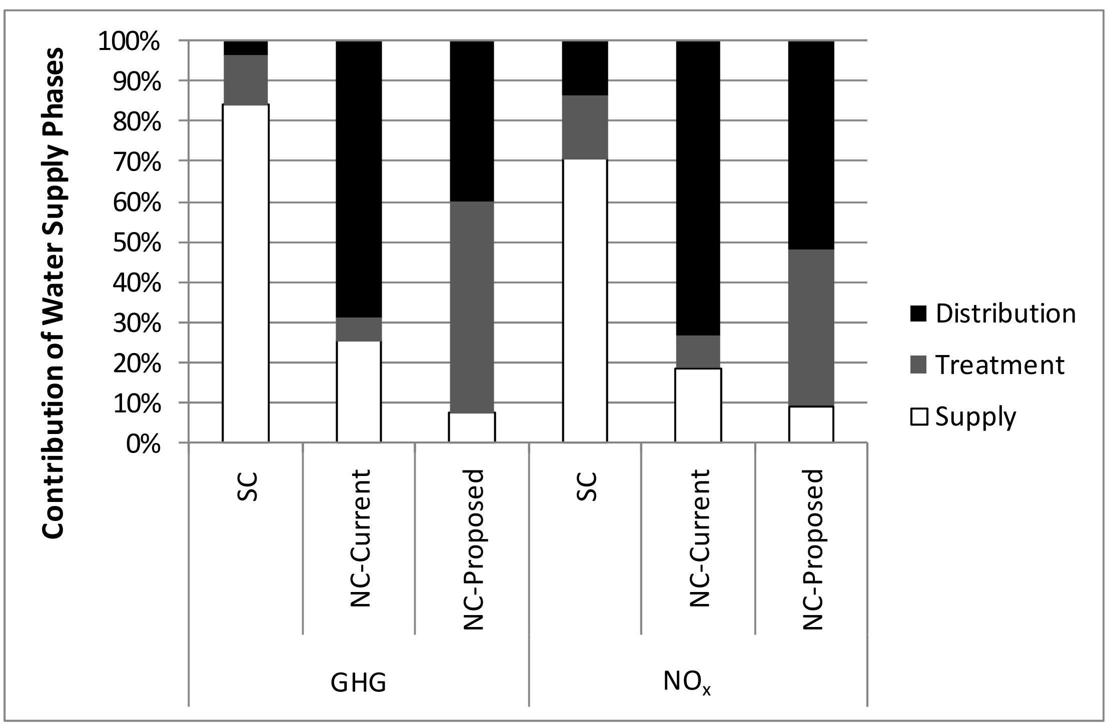


Figure 15: Water Supply Phase Results for Utilities



Supply is the most significant water supply phase for SC. The result reflects the large contribution of imported water. For the NC-Current system, distribution is most important because of its complexity. The topography of the service area is hilly so the communities served are spread out and water must be pumped between elevations. However, for the NC-Proposed system, treatment is also a significant contributor to the overall results, comparable to the distribution system, because of the energy-intensive desalination process.

Since WEST was created in 2004, many changes have been made to the tool. The results of this study were different from those reported in (Horvath 2005) for some chemicals and environmental effects. In addition, due to additional changes made to the tool and to case study assumptions through the course of the project, the results in this chapter are different from the final case study results reported in Chapter 12.

A summary of the changes to WEST which have affected the final results follows:

1. The revision to the allocation of materials to the construction and maintenance phases generally reduced the contribution of material production to the results. The original calculation double-counted some purchases. The revised calculation assigns the first purchase to the construction phase and all future costs to the maintenance phase, eliminating double-counting. The change reduces the number of purchases, affecting material delivery and fuel production. The results changed most for sources with significant maintenance requirements (e.g., the NC-Proposed's desalination system).
2. The inclusion of the life-cycle effects of electricity production significantly changes results for SO_x, NO_x, VOCs, and CO. For these chemicals, the "upstream" contributions to natural gas generation, California's largest source of electricity, are more than four times the direct emissions. For PM, the "upstream" contributions are approximately equivalent to the direct emissions.
3. The update to Year 2004 eGRID data affected the following EFs for California: NO_x decreased 40 percent, SO_x decreased 25 percent, and GHGs increased 11 percent.

In addition, EFs for VOCs and PM in California's electricity production were assumed to be zero before the life-cycle effects were incorporated. Now these values are available in the tool.

The explanations listed above will be referred to be number in the discussion that follows. Overall, the original results for energy, GHG, and NO_x changed the least. Generally the new results for these chemicals were higher as a result of (1). For NO_x emissions due to desalination and for the NC's recycled water systems, the new emissions decreased. These systems require significant maintenance and were affected by (1). Because of (2), one might expect that NO_x emissions would have increased more dramatically. However, the reduction in the overall EF (3) limited the growth of NO_x emissions.

The new results for SO_x, VOCs, PM, and CO were significantly higher than the previously reported values, in some cases increasing by a factor of more than six. The primary reason for the increased emissions is (2). The emissions associated with processes that require significant maintenance increase the least due to (1). The emissions for PM did not increase as much on average as for the other chemicals because the PM EF for the California electricity mix is exceptionally low (0.08 g/kWh). The national average for PM is 1.72 g/kWh.

5.3 Task 5 Conclusions and Recommendations

The revisions completed for Task 5 make important improvements to WEST. The revised EFs for electricity capture a more complete picture of the environmental effects, including energy use and GHG emissions. The energy use factor for lifecycle effects is twice the direct energy use factor. The GHG lifecycle EF for the average California mix is approximately 50 percent larger than the direct EF. Without including these lifecycle emissions, the effects of water provision would be significantly underestimated.

The addition of the sludge disposal activity is also important. Though the effects of sludge disposal are generally small compared to the overall results, in most cases less than one percent, certain disposal choices can reduce overall GHG emissions, if only by a small amount relative to the utility's total GHG emissions. One study found that for a large utility which serves over one million people, the total difference in GHGs between sludge disposal in a landfill that uses gas for electricity and one with no gas recovery system is 300 Mg annually (Stokes and Horvath 2010), equivalent to the emissions from 60 typical cars in a year (USEPA 2000).

Utilities can carefully review disposal options if the aspire to reduce their overall GHG emissions. However, changes to sludge disposal will not be as significant as other choices, including chemical selection and electricity sources.

CHAPTER 6:
Task 6 – Evaluate Demand Management and Conservation Measures

This task was designed to quantify the effects of reducing water demand using conservation programs. Many utilities develop programs to reduce water demand rather than develop new water supply, believing conservation programs are cost- and environmentally-effective measures (Gleick et al. 2003). These may include residential water-efficient fixtures and appliances, rain collection systems, irrigation systems, and commercial and industrial conservation technologies.

Urban water use in California is increasing, in part because a growing population creates more customers but also as individual water use increases. The average per capita water use in the state was 20 percent lower in 1960 than in 2000 (Hanak 2005). Economic growth means that Californians and others live in larger houses on larger lots with more water-using appliances, all increasing overall water use. Because water supplies statewide are limited, conservation or demand management strategies may delay, if not completely prevent, severe shortages of water or developing new, more expensive sources of water supply.

The researchers completed an assessment of available demand management (or water conservation) strategies using a life-cycle perspective to determine the relative effects of each and, in certain cases, how they compare to non-conserving alternatives. The goal of this research is to supplement previously conducted work about conservation potential, nationwide and in California specifically (e.g., (Mayer et al. 2000; Gleick et al. 2003; Mayer et al. 2003; Mayer et al. 2004; Aquacraft 2005). These prior studies focused on the economic motivations for conservation, emphasizing that conservation was less expensive than constructing new supply.

Task 6 furthered the analysis by translating the monetary investments in new water supply and water conserving strategies into the life-cycle environmental impacts of producing the infrastructure and materials needed to implement them. For the conservation strategies, the environmental effects of avoided water supply or energy generation were subtracted from the material production results. Energy generation is important for strategies that also provide additional energy efficiency or that avoid energy needed for water heating. These effects were quantified for several scenarios (e.g., the air emissions associated with installing a new fixture, replacing a fixture halfway through its life, and replacing a fixture at the end of its life). Furthermore, the environmental effects were converted into monetary units and compared. This methodology results in a more complete picture of the full costs associated with water provision and with water demand management strategies.

To provide context for California's current water use and conservation potential, general data were obtained from a Pacific Institute report assessing water end use and fixture market penetration (Gleick et al. 2003). Duplication of this analysis was beyond the scope of this task so these data have not been verified by the authors and are presented for informational purposes only. There is debate over the accuracy of these estimates (e.g., [Chestnutt and Pekelney 2004]);

however, they are useful indicators of the magnitude of water use for each end use. Table 20 summarizes the overall potential for water conservation according to the original report in units of million liters (Ml) per year.

Table 20: Summary of Conservation Potential

Sector	Estimated Year 2000 Use (Ml/yr)	Conservation Estimate (Ml/yr)	Reduction Potential (%)	Minimum Cost Effective Reduction (Ml/yr)
Residential Indoor	2,800,000	1,100,000	39%	1,100,000
Residential Outdoor[1]	1,800,000	580,000	32%	580,000
Commercial/ Industrial/ Institutional	3,100,000	1,200,000	39%	810,000
Unaccounted water	1,200,000	--		
Total	*8,900,000*	*2,880,000*		*2,490,000*

Notes:

[1] Value reported is average of the range reported in the original source.

Source: Gleick et al. 2003

The researchers analyzed indoor residential options, outdoor alternatives, and commercial, institutional, and industrial (CII) demand management strategies. A discussion of the general methodology is followed by the specific analysis for each end use.

6.1 Task 6 Approach

The analysis determined the life-cycle energy and air emission impacts of water demand management programs. The analysis focused on producing appliances, fixtures, and other materials needed to conserve one kiloliter per day (kl/d; approximately 264 gallons per day [gpd]) for a period of 20 years. Twenty years was selected as the planning horizon because it is the time frame associated with the Urban Water Management Plans which utilities must publish every 5 years. Results from previous analyses of NC-Current's water supply system were converted to this functional unit and time horizon so the results could be compared on an equivalent basis.

The analysis used LCA. The first step in the analysis was to inventory the material and energy requirements to meet these conservation goals, i.e., the number of appliances or fixtures necessary to conserve a kl /d for a period of 20 years was determined. Next, the economic costs of these fixtures for the consumer were calculated based on the estimated purchase price. The economic savings associated with conserved water and, when applicable, energy efficiency were also included. The equations used and sample calculations are included in Appendix F.1.

EIO-LCA EFs were used to estimate the environmental effects of manufacturing water-conserving equipment (CMU 2005). EIO-LCA allows the user to input a production cost for a product or service (in $), select the appropriate economic sector, and automatically calculate economic and environmental effects throughout the product's entire supply chain. The following effects can be calculated: energy use and GHGs, NO_x, PM, SO_x, VOC, and CO. Table 21 provides the relevant EIO-LCA EFs. Equations and summary calculations used in the analysis are described in Appendix F.1.

Table 21: EIO-LCA Emission Factors by Sector

Sector	Energy MJ/$	GHG g/$	NO_x g/$	PM g/$	SO_x g/$	VOC g/$	CO g/$
Vitreous china plumbing fixture, china & earthenware bathroom accessories manufacturing	13	890	1.5	0.24	1.5	1.0	8.6
Enameled iron & metal sanitary ware manufacturing	8.5	640	1.3	0.34	1.7	0.75	5.0
Iron & metal sanitary ware + semiconductors (infrared sensors; custom sector)	8.5	640	1.3	0.36	1.9	0.80	5.2
Plastics plumbing fixture manufacturing	11	810	1.8	0.28	2.0	2.0	7.2
Household laundry equipment manufacturing	9.9	810	1.7	0.58	1.9	1.9	8.7
Laundry + electronics (custom sector)	10	810	1.7	0.58	1.9	1.9	8.7
Natural gas distribution	14	2200	2.5	0.23	2.3	5.3	4.3
Fertilizer, mixing only, manufacturing	37	3200	4.9	0.85	3.3	2.7	13
Greenhouse & nursery production	8.1	770	2.1	1.40	1.8	1.5	12.0
Water, sewage, & other systems	11	7800	1.1	0.13	1.3	3.8	2.2
Industrial process variable instruments	4.2	340	0.72	0.21	0.89	0.59	3.6
Plastics pipe, fittings, & profile shapes	15	1100	2.3	0.31	2.5	2.4	9.6
Sawmills	8.3	710	2.4	5.0	1.4	5.3	38
Ready-mix concrete manufacturing	22	2000	7.9	1.0	6.3	5.6	17
Iron & steel forging	13	1100	1.9	0.72	2.4	1.1	8.7
Paint & coating manufacturing	16	1200	2.0	0.74	2.2	2.9	9.9
Fabricated structural steel manufacturing	9.4	830	1.6	0.68	2.0	1.0	8.9
Steel wire drawing	14	1300	2.3	1.00	2.6	1.4	14.0
Watch, clock, & other measuring & controlling device manufacturing	5.7	450	0.9	0.32	1.6	0.7	5.1
Metal valve manufacturing	6.6	530	1.1	0.37	1.6	0.7	5.1
S&, gravel, clay, & refractory mining	19	1300	1.9	0.29	2.9	0.7	3.7

Source: Carnegie Mellon University 2007

The user enters material production costs, rather than consumer prices, into EIO-LCA. It is difficult to determine accurate producer prices when a wide range of materials are required.

Unless otherwise noted, producer costs are assumed to be 60 percent of the consumer price for all materials.

To allow comparison of water conservation alternatives on an economic basis, the air emissions are translated into dollars using estimates of their external costs from (Matthews and Lave 2000). Matthews conducted a literature survey to determine the range of external cost estimates for these air emissions. Table 22 provides the ranges; median values were used for the calculations. Equations and sample calculations are shown in Appendix F.1.

Table 22: External Cost Estimates

	External Costs ($/Mg of Air Emissions)			
Effect	**Minimum**	**Median**	**Mean**	**Maximum**
GHG	2	14	13	23
NOx	220	1,100	2,800	9,500
PM	950	2,800	4,300	16,000
SOx	770	1,800	2,000	4,700
VOC	160	1,400	1,600	4,400
CO	1	520	520	1,100

Source: Matthews and Lave 2000

The evaluation also estimates the economic and environmental effects of avoided water and energy. The economic analysis uses East Bay Municipal Utility District's (EBMUD) water and sewer costs (1.4 cents/ℓ or 3.66 per thousand gallons [gal.], from [Aquacraft 2005]) and Pacific Gas and Electric's electricity and natural gas costs ($0.114/kWh and $1.3/therm, respectively, based on a 2007 residential consumer bill). These results were compared to the emissions associated with supplying water based on previously analyzed case study data.

Typical water supply costs used for comparison were obtained from (MWD 1996). Emission factors for natural gas distribution, used primarily to assess natural gas water heaters, are from EIO-LCA (see Table 21). Energy emissions for electricity were obtained from the October 2007 version of WEST. Emissions factors for water supply are based on results from the NC-Current case study. The water and electricity EFs were presented and discussed in Chapter 6.

Several scenarios were considered during the economic analysis, as appropriate:

- Full purchase: Evaluation uses 100 percent of the economic costs for the purchase costs and 100 percent of the associated environmental effects of production.
- Early replacement of fixture: Evaluation assumes half of the economic life remains in the fixture. Evaluation uses 50 percent of the economic costs and 50 percent of the associated environmental effects.

- Marginal costs of fixture: In some cases, an average fixture and a water-conserving fixture which are otherwise comparable are produced by the same manufacturer (e.g., washing machine). Evaluation assumes a fixture will inevitably be purchased; therefore, the evaluation uses the difference in the economic costs of the two machines for the purchase costs and an estimate of the marginal production costs specific to the product for the associated environmental effects.
- End-of-life replacement of fixture: Evaluation excludes purchase costs and the associated environmental effects of production because they are considered inevitable.

Any exceptions to these scenarios are discussed below. Assumptions, equations, and calculations are summarized in Appendix F.

6.1.1 Indoor Demand Management Approach

Indoor demand management was targeted as the initial and most detailed analysis for two reasons. First, there is significant potential for consumption reduction (see Table 20). Second, the strategies for reduction are easily-defined and fairly uniform between homes. Conversely, the other major area for water conservation potential, the CII sector, requires different strategies for each industry type and can be facility-specific. The CII sector is therefore difficult to analyze.

Indoor water use estimates broken down by fixture are shown in Table 23. The data in this table were taken from (Gleick et al. 2003). Since they are used only for illustrative purposes, the data have not been verified by the authors. The indoor demand management assessment included toilets, showerheads, faucets, and washing machines. Leaks are another major source of household wasted water. A large portion of the leaks in homes occur at toilet flappers. Retrofitting toilets repairs these leaks and reduces overall water use. Water conserved through toilet leak repair is discussed and analyzed in the "Toilets" section.

Table 23: Summary of Indoor Water Use

Fixture	Estimated Year 2000 Use (Ml/yr)	Fraction of Indoor Use (%)	Estimated Cost Effective Savings (Ml/Yr)	Reduction below Current Use (%)
Toilets	910,000	40%	520,000	57%
Showers	610,000	27%	150,000	25%
Washing Machines	410,000	18%	140,000	34%
Dishwashers	30,000	1%	16,000	53%
Leaks	350,000	15%	280,000	80%
Faucets	520,000	23%	-	
Total	*2,800,000*	*123%*	*1,100,000*	*39%*

Source: Gleick et al 2003

Performance data for fixtures and appliances were obtained from a series of residential water conservation studies performed by Aquacraft, Inc., Water Engineering and Management of Boulder, Colorado (Mayer et al. 2000; Mayer et al. 2003; Mayer et al. 2004; Aquacraft 2005). These studies were completed in three utility service areas (Seattle Public Utility [SPU] in Washington; EBMUD in the vicinity of Oakland, California; and Tampa Water Department [TWD] in Florida) between 1999 and 2004. In addition to reports for these utilities individually, one final overview report was produced in 2005 for the U.S. EPA. The studies are collectively referred to as the "Aquacraft reports or studies".

Each study included approximately 30 single family homes. Water use was analyzed for a period of approximately two weeks to provide baseline data. Then new water conserving fixtures were installed and water use was analyzed for two additional two-week periods. Key parameters of each study are summarized in Table 24.

Table 24: Aquacraft Studies Summary

Study Details	SPU	EBMUD	TWD
Homes studied (#)	37	33	26
Water prices (per thousand gal)	$11.27	$3.66	$5.67
Average home size (square feet)	1879	2054	1627
Occupancy (people/hh)	2.51	2.75	2.92
Total Base-line Water Use (kl/yr)	209	259	266
Total Post-Retrofit Water Use (kl/yr)	128	171	144
Reduction (%)	39%	34%	46%

Source: (Mayer et al. 2000; Mayer et al. 2003; Mayer et al. 2004)

Table 24 illustrates some differences inherent in the three studies. Aquacraft conducted a statistical analysis on the results of the three studies and determined that differences in home size and occupancy affected total household water use in a statistically significant way. Water prices were not found to be significant to the changes in water use. However, the lower prices in EBMUD and TWD may explain in part why baseline water use in these areas was higher.

Some difference in "fixture" performance may actually be attributed to the study location and overall water use patterns in that area. The utility where each fixture was used is listed in the table of the fixture's performance data. However, the Aquacraft data were used regardless of these shortcomings because these data were the best available. For our analysis, the average performance data from the three studies were used unless otherwise noted. Customer satisfaction ratings for the fixtures themselves are provided (when available) to demonstrate that the performance of different models was comparable.

The following sections discuss the assumptions and data used to analyze the indoor conservation fixtures included in this study: low-flow toilets, showerheads, faucets, and washing machines. Assumptions, equations, and calculations are summarized in Appendix F.1.

6.1.1.1 Low-Flow Toilets

The Federal Energy Policy Act (FEPA) of 1994 mandated that all toilets purchased have a maximum flush volume of 6.1 l or 1.6 gal. Toilets with higher rated flush volumes are no longer available. However, as toilets age, their performance deteriorates. As a result, low-flow toilets may use more than their rated flow of water.

The three Aquacraft studies analyzed the performance four types of toilets listed with their rated water use: standard gravity flush (6.1 l per flush [lpf], dual flush (user selects either 3 lpf or 6.1 lpf), pressure-assisted flush (4.2 1pf or 1.1 gpf), and a flapperless flush (6.1 lpf). A pressure assisted flush toilet was included in the Aquacraft study. They analyzed a St. Thomas Creations toilet that used a Sloan Flushmate 1.1 insert. However because only two models were used, performance data were not reported. Information on the model used in the original study could not be found. Instead, a Kohler Wellworth, also with a Sloan Flushmate 1.1 insert, was analyzed. The performance and price data are based on manufacturer's information rather than results reported by Aquacraft . Table 25 summarizes the relevant data for all toilet models.

Table 25: Toilet Performance Data

Parameters	Gravity flush	Dual flush	Pressure-assist flush	Flapperless flush
Sample Model	Toto Drake	Caroma Caravelle 305	Kohler Wellworth Pressure Lite[1]	Niagara Ultimate
Rated Water Use (lpf)	6.1	3.0/6.1	4.2	6.1
Actual Water Use (lpf)[2]	5.8	4.9	4.2	6.1
Flush frequency (f/toilet/d)[3]	6.7	7.6	7.4	7.2
Water saved (l/toilet/yr) vs.	22385	33367	57305	54119
Water saved (l/toilet/yr)	657	3371	5255	0
Toilets Needed[5]	13	8	5.1	5.5
Purchase Price[2]	$ 280	$ 350	$ 440	$ 165
Utility where Studied	SPU, EBMUD	SPU, EBMUD	EBMUD	EBMUD, TWD
Consumer Satisfaction Rating[6]	4.67	4.31	--	4.67
Payback period[2,7]	3	3.5	--	2.3

Notes:
[1] The EBMUD study considered a Sloan Flushmate insert into a toilet by St. Thomas Creations, rather than Kohler., but the efficient flushing mechanism is identical. Flush volume is based on manufacturer estimate rather than Aquacraft study results. Purchase price from internet search.
[2] Calculated or reported by Aquacraft (Aquacraft 2005), except as noted elsewhere.
[3] Calculated by the authors based on reported Aquacraft data
[4] Water saved reported by Aquacraft includes water saved due to leak repair during installation.
[5] Number of toilets needed to conserve 1000 l/d above baseline over a 20 year period.
[6] Consumers rated the equipment on a scale of 1 (poor) to 5 (good).
[7] Payback period is calculated for net replacement, using 50% of purchase price.

The analysis assumed that each home had two toilets with a service life is 25 years. The number of toilets per household was not explicitly provided in the Aquacraft studies but the two-toilet assumption is consistent with their data. A literature review indicates toilet service life estimates range from 20 to 40 years. The 25 year assumption is conservative.

Much of the water used in toilets is lost by leaks, especially at the toilet flapper. In the Aquacraft study, their estimates of household water conservation included savings for toilet flushing and leak repair. The analysis includes the benefit of repairing leaks. As a result, the conserving nature of these toilets may be over-stated on an individual basis (i.e., a home without a leak will not conserve the estimated water volume) but is indicative of the conservation on a larger scale.

The EIO-LCA sector "Vitreous China Plumbing Fixture and China and Earthenware Bathroom Accessories Manufacturing" was used to determine emissions associated with toilet production.. Ceramic parts were assumed to be the major contributors to the results and to be comparable for all models. Because toilets use only cold water, there is no energy savings associated with more efficient toilets.

6.1.1.2 Showerheads

FEPA mandates that showerheads must have a flow rate less than 9.5 liters per minute (lpm, 2.5 gal. per minute [gpm]). The Aquacraft baseline study indicated water use is already below the mandated flow rate even when conserving showerheads are not used. For the three studies, the baseline flow rate ranged from 7.6 to 8.5 lpm, indicating the average users do not use the full flow range. Four models of low-flow showerheads were analyzed by Aquacraft. Two models were standard 9.5 lpm models, one was a 6.6 lpm model, and the last was a hand-held model with a 8.9 lpm flow rate. Detailed data used in the analysis are provided in Table 26.

Table 26: Showerhead Performance Data

Parameters	Brasscraft LF	AM Conservation Spoiler	Niagara Earth[1]	Niagara Earth Handheld[1]
Rated flow (lpm)	9.5	9.5	6.6	8.9
Actual flow (lpm)[2]	7.1	6.9	6.2	8.3
Shower use (min/day)[4]	5.0	7.3	10.4	10.4
Water saved (l/yr) vs. baseline[2]	1,382	2,082	6,596	678
Water saved (l/yr) vs. 9.5 lpm standard[3]	4,400	7,100	12,000	4,400
Shower-heads needed[4]	423	281	105	109
Purchase Price[5]	$18	$14	$17	$30
Utility where studied	SPU	EBMUD	TWD	TWD
Consumer satisfaction rating[6]	4.58	4.43	4.44	4.44
Payback period[7]	1.5	3.1	0.75	0.75

Notes:
[1] Water use for Niagara showerheads were reported together and disaggregated by the authors as described in Appendix F. Satisfaction ratings for Niagara showerheads were not disaggregated.
[2] Calculated or reported by Aquacraft (Aquacraft 2005)
[3] Calculated by the authors based on reported Aquacraft data
[4] Number of showerheads needed to conserve 1000 l/d above baseline over a 20 year period.
[5] Purchase prices based on internet search.
[6] Consumers rated the equipment on a scale of 1 (poor) to 5 (good).
[7] Payback period is calculated for net replacement, using 50% of purchase price.

Each home was assumed to have two showerheads. The service life of each showerhead was assumed to be 12.5 years based on the Aquacraft studies. Aquacraft reported the performance for the two Niagara showerheads in aggregate. The authors disaggregated the data based on the expected flow rate using calculations described in Appendix F.1. The showerheads studied were primarily plastic construction; the EIO-LCA sector "Plastics Plumbing Fixture Manufacturing" was used in the analysis.

Surprisingly, Aquacraft indicated the reduced flow did not reduce overall hot water use in an statistically significant way. As a result, no energy savings were calculated for showerheads.

6.1.1.3 Faucets

Two types of conservation measures were used for faucets: aerators and hands-free devices. Faucet aerators are installed on existing fixtures to restrict flow. The two hands-free devices functioned differently. The first device was a faucet controller which required the user to lean on a pushbar or step on a pedal to activate the faucet; this device is used in addition to the existing faucet and, if applicable, aerator. The Aquacraft studies analyzed the Aqualean™ device (pushbar mechanism); however, the authors could not find price data for this device. Instead, price data is for a Pedalworks™ foot-activated device. Performance for both devices is expected to be similar. The second device (Delta e-flow) is a faucet with infrared sensors to activate the faucet. Both mechanisms prevent water from running continuously when not needed. Table 27 includes the relevant information for analyzing the faucet systems.

Table 27: Faucet Performance Data

Parameter	New Resources Group	Niagara	Hands-free faucet controller[1]	Delta e-Flow hands-free faucet[2]
Rated Water Use (lpm)[3]	8.3 (k), 5.7 (b)	5.7 (k), 3.8 (b)	--	--
Actual flow (lpm)[4]	3.7	2.8	--	2.7
Faucet use (min/d)[5]	29	28	--	33
Water saved (l/yr) vs. baseline[4]	4,160	13,749	2,017	11,368
Household Sets of Faucets	88	27	181	32
Puchase Price[7]	$3	$6	$290	$317
Energy saved vs. baseline (kWh/yr)/(therm/yr)[8]	55 / 35	83 / 140	11 / 18	75 / 130
Utility where Studied[9]	Seattle	Tampa	Tampa	Tampa
Satisfaction Rating[10]	4.39	4.3	4.7	3.79
Payback period[4,11]	2	0.77	--	12.4

Notes:

[1] No information was found about the Aqua-lean hands-free faucet controller from an internet search. Price is for a PedalWorks™ hands-free faucet control. Performance of these devices is assumed to be similar. Aqua-lean performance indicated the device conserved an additional 0.5 gal/person/day; the marginal savings is the only water included in the analysis.

[2] The purchase price listed reflects the total purchase price ($317) minus the cost of a comparable, non-hands-free Delta model ($119), as reported by Aquacraft.

[3] Abbreviations: (k) = kitchen, (b) = bathroom

[4] Calculated or reported by Aquacraft (Aquacraft 2005)

[5] Calculated by the authors based on reported Aquacraft data

[6] Number of devices needed to conserve 1000 l/d above baseline over a 20 year period.

[7] Purchase prices based on internet search and is the lowest cost for bulk purchases, when available.

[8] Calculations and assumptions for hot water calculations are described in Appendix F.1.

[9] EBMUD study results were not included because faucet use did not cause a statistically significant reduction in water use.

[10] Consumers rated the equipment on a scale of 1 (poor) to 5 (good). It the appliance was used by multiple utilities, average ratings are listed.

[11] Payback period is calculated for net replacement, using 50% of purchase price.

All faucet control devices were analyzed using the EIO-LCA sector is "Enameled Iron and Metal Sanitary Ware Manufacturing." Aquacraft reported most homes had one kitchen faucet and two bathroom faucets. In most cases, aerators installed in the kitchen allowed a higher flow rate than aerators installed in the bathroom. However, the flow trace software used by Aquacraft to complete their water use assessments could not distinguish between water used in the kitchen and in the bathroom. Therefore, the results could not be disaggregated and faucets were analyzed on a household basis rather than for each individual fixture.

For the two hands-free devices, the standard assumption that producer price is equivalent to 60 percent of consumer price was not appropriate. The hands-free pedal or push bar is a device made of standard plumbing equipment. The simplicity of the fixture indicates the $290 price tag reflects a significant markup over the producer costs. The producer price was assumed to be 10 percent of the consumer price in the EIO-LCA analysis for this fixture.

Similarly, the Delta eFlow device cost $319 while a comparable Delta faucet cost $119. The infrared sensor added to the faucet does not account for the $200 markup. In the EIO-LCA analysis for this product, the lower price of $119 was used in the assessment; 10 percent of the semiconductor sector EF (g/$) was added to the standard EF for metal sanitary ware to account for the added infrared sensor, effectively assigning the sensor a cost of $11 per unit. Aquacraft did not report an overall household savings for the Aqua-lean faucet controller. They reported the devices saved an additional 1.9 l/d (0.5 gpd) per person, however only two fixtures were installed so the results were less robust.

The overall water flow reduction also reduced hot water use and, therefore, energy use. Hot water use was analyzed specifically in Aquacraft's SPU and EBMUD studies, but not in the TWD study. The estimates of hot water consumption in SPU and EBMUD were used to allocate the reduction in hot water use for the TWD study. The calculations used the water and energy costs for the EBMUD (California) service area. It was assumed that 80 percent of hot water heaters use natural gas (65 percent efficient) and 20 percent use electricity (93 percent efficient). Because electricity costs are higher than natural gas, these assumptions are fairly conservative.

6.1.1.4 Clothes Washing Machines

Clothes washing machines are not subject to federal regulation. Consumers can freely choose more or less efficient machines. Washing machines on today's market vary widely in their water consumption, from less than 75.7 l/load to more than 170 l/load (20 gal./load to >45 gal./load) based on an internet search. In addition, water-conserving machines reduce hot water use, resulting in additional energy savings. Some machines may be more energy efficient. Many consumers do not purchase water-conserving machines because the first costs are higher than a comparable non-conserving machine, even though life-cycle costs can be lower. Six washing machines models were examined in the Aquacraft reports. Some models were top-load (or vertical axis) machines, while others were front-load (horizontal axis machines). Table 28 includes the assumptions associated with washing machines included in this analysis.

Table 28: Washing Machine Performance Data

Parameter	Maytag Neptune	Frigidaire Gallery	Whirlpool Super Capacity+	Fisher & Paykel Ecosmart	Whirlpool Duet	Whirlpool Calypso
Actual water use (l/load)[1]	94	88	109	111	68	103
Washer use (load/d)[1]	1.1	0.91	0.82	0.93	1.2	1.0
Water saved (l/yr) vs. baseline[1]	16,000	22,400	21,300	15,800	30,300	23,500
Machines Needed[2]	35	26	31	35	19	24
Purchase Price[3]	$1,066	$682	$550	$699	$999	$899
Comparable Machine Cost[3]	$516	$207	$489	$500	$550	$450
Energy savings (kWh/yr) / (therm/yr)[4]	320 / 21	200 / 13	200 / 14	290 / 19	190 / 13	200 / 13
Utility where Studied	SPU	SPU, EBMUD	SPU, EBMUD	EBMUD	TWD	TWD
Type	Front load	Front load	Top load	Top load	Front load	Top load
Satisfaction Rating[5]	4.81	4.38	4.81	4.65	4.84	4.83
Payback period[1,6]	5.9	2.5	1.0	2.9	5.7	5.5

Notes:

[1] Calculated or reported by Aquacraft (Aquacraft 2005)

[2] Number of washing machines needed to conserve 1000 l/d above baseline over a 20 year period.

[3] Purchase prices and comparable machine costs reported by Aquacraft; when machine is used in multiple studies, the lowest cost is used.

[4] Results determined using a calculator on the (Energy Star 2007) website; includes energy for water heating.

[5] Consumers rated the equipment on a scale of 1 (poor) to 5 (good). It the appliance was used by multiple utilities, the satisfaction ratings are averaged.

[6] Payback period is calculated for net replacement, using 50% of purchase price.

Water conserving machines are marketed as "green", resulting in a price markup. Some of these machines do contain more sophisticated electronics than a comparable non-conserving machine. For washing machines, a part of the "Household Laundry Equipment Manufacturing" EIO-LCA sector, it was assumed that the cost of production was similar to the purchase price of a non-conserving comparable machine. The contribution of the "electronics" sector to the overall supply chain was doubled for high-efficiency washer, a conservative assumption. The custom EF used for washing machines is shown in Table 21.

Energy savings were calculated using the Energy Star life-cycle costs calculator for washing machines developed by the U.S. EPA and U.S. Department of Energy (Energy Star 2007). The analysis assumed 80 percent of the machines were supplied by gas water heaters and the remaining by electric, as discussed in the "faucets" section.

6.1.2 Commercial, Industrial, and Institutional Demand Management Approach

There is great potential for conservation by non-residential consumers, namely in the CII sectors. However, the activities of all the business and entities included under this umbrella are more diverse than the activities of a household. As a result, a comprehensive analysis of many of the conservation strategies in these sectors is beyond the scope of this task. Instead, a few representative strategies were chosen and analyzed.

To analyze the potential water savings in the CII sectors, a scenario for replacing toilets and urinals in an office building with low-flow devices was analyzed. Outdoor conservation strategies for the CII sector are discussed with other Outdoor strategies.

To show the potential for indoor water conservation, installing waterless urinals/ultra-low flow toilets in an office building was analyzed. This analysis evaluated a hypothetical 15-story office building in Oakland, California. Each floor had 557 m^2 (6,000 sq. feet) of office space, housed 175 employees (50 percent male/female), and had seven toilets and two urinals. Each employee was assumed to flush either a toilet or urinal three times a day (women always use a toilet; men use a toilet once and urinal twice daily) (Vickers 2001). The authors assumed employees worked 245 days a year (49 work weeks) and the number of flushes did not change with the retrofits.

The original fixtures were assumed to use water at rates typical prior to the 1994 legislation: for toilets 13.2 lpf and urinals 5.7 lpf. Based on these assumptions, the fixtures would use an average of 14,300 and 3070 kl/yr, respectively. Two water conserving toilets and two urinals were compared. The toilets used 1.6 gpf and 1 gpf; the urinals evaluated were a 1 gpf model and a waterless urinal. The waterless urinal analyzed required a trap seal liquid chemical be used every 1500 flushes for maintenance. This chemical may not be required for all models. Table 29 summarizes the models used in this study. Toilets were assumed to have a life of 25 years, urinals 20 years. The total economic cost for all fixtures includes an installation cost of $100 per fixture. Calculations and further details are available in Appendix F.2.

Table 29: Office Building Fixture Details

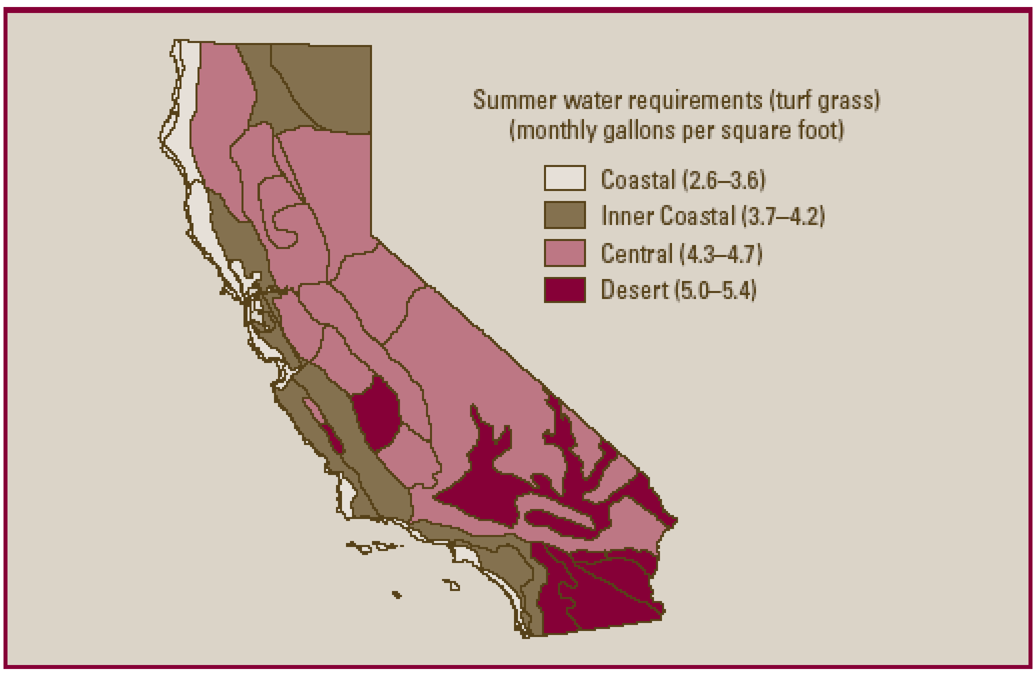
	Toilets		Urinals	
	Toilet 1	Toilet 2	Urinal 1	Urinal 2
Water Use (lpf)	61	3.8	3.8	0
Fixture price	$165	$440	$250	$450
Chemical ($/yr)	--	--	--	$25
Water savings (kl/yr)	65	85	34	102

6.1.3 Outdoor Demand Management

Customers consume water outdoors for a variety of reasons, including irrigation, car washing, and to supply water features. Outdoor water use is estimated as just under half of indoor use for residential customers nationwide (Vickers 2001). However, water use varies depending on land use, landscape, and climate. In California, summer outdoor water use ranges from 105 liters per square meter per month ($l/m^2/month$) in cooler, coastal areas to 220 $l/m^2/month$ in desert regions (Hanak and Davis 2006). The total residential outdoor water use in the United States is approximately 100 billion l/d (26 billion gpd) and will continue to increase as the population grows (Vickers 2001). In California, the population is expected to grow by more than 11 million people in 2030. Nevertheless, the outdoor residential water savings potential (32 percent) is significant (see Table 20).

One information source defined four evapotranspiration zones for the state which are used to estimate water needs in the differing climates. The four zones (coastal, inner coastal, central, and desert) are shown graphically on Figure 17. The regions are defined based on their summer water evapotranspiration characteristics for turf grasses; these characteristics are the baseline for all water requirement estimates and are referred to as "E0". Turf grasses are a high water-using plant. Water requirements in other seasons and for most other plants are correspondingly lower. Constants are used to estimate the annual water needs for each scenario relative to the E0 baseline. Figure 16 provides ranges for estimates of E0 for each region.

Figure 16: Evapotranspiration Superzones



Source: Hanak and Davis 2006

Consumers and water agencies can choose from demand management strategies to minimize or control outdoor water use. However, most strategies involve some material and energy inputs and also offset water supply and sometimes energy production, all of which have energy and environmental effects. LCA is used to compare these alternatives based on a functional unit of one kl/d over a period of 20 years, similar to the assessment for indoor demand management.

Outdoor demand management strategies evaluated include: turf maintenance, drip irrigation, on-site smart controllers, xeriscaping, dormant turf, rain runoff catchment, graywater systems, and water pricing options. Each alternative was evaluated for the following seven scenarios:

- An average-sized single-family home and lot in the coastal region (SF1);
- An average-sized single-family home and lot in the inner coastal region (SF2);
- An average sized single-family home and lot in the desert region (SF3);
- A single-family home on a large lot ("ranchette") in the central region (SF4);
- A hypothetical multi-family unit in the coastal region (MF);
- A commercial facility similar to a big box store in the desert region (COM); and
- A 40,000 m2 (10-acre) industrial site in the central region (IND).

Five residential scenarios were evaluated in this assessment. For each home, only a portion of the yard was assumed to be irrigated. The remainder was assumed to be covered with impermeable materials (driveways, sidewalks, patios) or left dormant. In addition, a percentage of the irrigated area was assumed to be turf (or grass) while the remainder was assumed to be other landscaping (e.g., trees, shrubs, and flowers). The baseline analysis assumes that the non-turf plants are divided evenly between low, medium, and high water using-plants. The residential scenarios are discussed further below; additional scenarios for commercial and industrial outdoor water use were also analyzed and are discussed in later sections.

Average-sized single family homes were assumed to irrigate 35 percent of their yard (Hanak and Davis 2006). These three scenarios were assumed to be located in the coastal region (San Franscisco, California), the inner coastal region (Pasadena, California), and the desert region (Palm Springs, California). A larger single-family home on a large lot, referred to as a "ranchette," assumed to be located near Fresno was analyzed for comparison. It was assumed that for a yard of this size only 10 percent is irrigated.

Another scenario analyzed a multi-family 20-unit building located in urban Los Angeles. The South Coast has the highest percentage of multi-family units in California (39.3 percent) (Hanak and Davis 2006). The multi-family home is assumed to irrigate 25 percent of the yard. The commercial scenario, modeling a large "big box" store assumed 3 percent of the yard area was irrigated; the industrial scenario, a manufacturing facility with landscaping, assumed 5 percent of the yard was irrigated. The data used in each scenario is described in Table 30. Detailed assumptions and calculations are described in Appendix F.3.

The outdoor water saving alternatives evaluated included: turf maintenance, drip irrigation, on-site smart controllers, xeriscaping, dormant turf, rain runoff catchment, graywater reuse, and water pricing. The water savings is based on the results of the baseline analysis for that scenario.

Table 30: Outdoor Water Use Scenarios

Scenarios	Region	Lot Size (m^2)	Irrigated Area (m^2)	Turf (% of irrgated area)	Summer Water Use (l/m^2/ month)	Annual Needs (l/m^2/yr)	Baseline water use (kl/yr)	Source
Residential								
Single-family1 (SF1)	Coastal	725	363	70%	110	748	208	(Hanek 2006), Average
Single-family2 (SF2)	Inner Coastal	836	465	75%	163	1,108	402	(Hanek 2006), Average
Single-family3 (SF3)	Desert	1,022	598	80%	212	1,441	686	(Hanek 2006), Average
Single-family4 (SF4)	Central	16,495	14,637	90%	183	1,247	3,122	(Hanek 2006), Large
Multi-family (MF)	Coastal	879	188	50%	116	790	64	Assumed
Commercial (COM)	Desert	90,968	2,729	50%	212	1,441	5,111	Assumed
Industrial (IND)	Central	40,467	40,467	60%	183	1,247	1,715	Assumed

6.1.3.1 Turf Maintenance

This scenario assumes that compost is applied to turf annually. Every ten years, a significant application is completed, where approximately four centimeters (cm, 1.5 in.) of compost is mixed with the topsoil to improve the health and drainage of the soil. In the intervening years, a layer of compost of 0.6 cm (0.25 in.) is applied. For non-turf landscaping, a layer of 5 cm (2 in.) of mulch is applied around the plant bases every two years. Compost materials are assumed to cost \$30/m^3; mulch, \$8/m^3. Compost and mulch are part of the EIO-LCA sector "Fertilizer, mixing only, manufacturing". This turf maintenance strategy is expected to reduce outdoor water use by 10 percent (Gleick et al. 2003).

6.1.3.2 Drip Irrigation

The drip irrigation system scenario assumes that non-turf landscaping is irrigated using the more efficient drip configuration. This method directs water near the base and roots of the plants and prevents unnecessary runoff or evaporation. Drip irrigation systems cost \$0.10/m^2 (Means 2004). Based on the cost guide, 85 percent of the cost was for tubing ("plastic pipe, fittings, and profile shapes" sector), 3 percent for screens ("steel wire drawing" sector), 5 percent for timers and controls ("watch, clock, and other measuring and controlling device manufacturing" sector). The remainder was for valves ("metal valve manufacturing" sector). Drip irrigation reduces water use for non-turf landscaping by 50 percent (Gleick et al. 2003). Drip irrigation is not an effective means of watering turf. The 50 percent reduction corresponds to an overall outdoor water use reduction of 3 – 19 percent, depending on the scenario.

6.1.3.3 On-site Smart Controllers

This scenario assumes on-site smart controllers (e.g., moisture sensor probes) determine when water is needed and are used to control the irrigation system. The term "on-site" distinguishes these systems from the more expensive satellite-controlled systems. These systems prevent irrigation when there has been recent rainfall, preventing over-watering or runoff, but are expensive and complex. Installing moisture sensors is expected to reduce overall outdoor water use by 20 percent (Gleick et al. 2003). It is assumed that the moisture systems will be used in conjunction with an existing sprinkler system if implemented. Each sensor costs $290 and is assumed to be a part of the "Watch, clock and other measuring and controlling device manufacturing" EIO-LCA sector. Four sensors were installed at the average single family home, seven at the "ranchette", and five at the multi-family building.

6.1.3.4 Rain Catchment

Rain catchment involves installing water storage systems, connecting them to a structure's gutters, and collecting the runoff from the roof for future use in irrigation. This strategy is arguably more appropriate in climates where rainfall occurs throughout the year than in California's climate where rainy and dry seasons exist. The storage capacity needed to store sufficient runoff in the winter for use three or more months later when the rain stops is more than the average residence reasonably can install due to space and cost limitations. However, these systems can still reduce overall water use, depending on the investment in storage. For residences, it was assumed that homeowners purchased a plastic container which stores 7,600 l (2,000 gal.). Each barrel is placed at gutter downspout locations and collects water until full, then redirects water away from the building. The cost of these containers is assumed to be $950 and the associated EIO-LCA sector is "Plastics plumbing fixtures and all other plastic products."

For CII scenarios, rain catchment for large facilities was assumed to occur in underground cisterns constructed of reinforced concrete. The cost of these cisterns is $0.09/l. The commercial facility used a cistern of 45,000 l (12,000 gal.) the industrial cistern held 34,000 l (9,000 gal.). The cisterns consist of the following materials, listed with their percentage contribution to the overall cost and the associated EIO-LCA sector: lumber primarily for forms (10 percent, "Sawmills"), concrete (60 percent, "Ready-mix concrete manufacturing"), reinforcing bar/mesh and lids/hatches (15 percent, "Fabricated structural metal manufacturing"), latex seal (5 percent, "Paint and coating manufacturing"), and pipes and accessories (10 percent, "Plastic pipe, fittings, and profile shapes"). The environmental costs associated with constructing the cisterns (e.g., emissions from construction equipment) were not included in the assessment. It is assumed that no new plantings or irrigation systems will be installed.

To evaluate the savings associated with rain catchment, rainfall data was used to calculate the water needed seasonally to irrigate the landscape. When rainfall exceeds need, two maximum storage volumes are assumed to be used during that period or stored for the future. Water savings associated with runoff collection ranges from 1 – 20 percent for residences. The savings for the commercial and industrial scenarios were 80 percent and 45 percent, respectively.

6.1.3.5 Graywater Systems

The graywater system assumes that non-potable piping is installed in each home or facility to collect water from sinks, showers, and washing machines for irrigation with little to no treatment. Greywater production is estimated to be 95 l/d (25 gpd) per person. It was assumed that production at the commercial facility was 0.4 l per customer. At the industrial facility, the 30 l/d estimate assumes there is some process water available for use. It was assumed that 80 percent of greywater production would be captured for reuse. Assumptions for savings from graywater were limited by irrigation needs not met by rainfall. Since greywater storage is not recommended for health reasons, only 1,000 l of graywater were assumed to be needed at single-family residences during seasons when rainfall exceeded landscaping needs. For other facilities, the volume was doubled. It was assumed that this water was used between rain events. Piping costs (interior and exterior) for the non-potable water system were scaled based on the size of the facility. Graywater systems consisted of plastic barrels and piping ("Plastics plumbing fixtures and all other plastic products"), filters ("Sand and gravel"), and valves ("Metal valve manufacturing").

6.1.3.6 Xeriscaping

This scenario involves reducing the overall percentage of turf to 30 percent of the landscaped area for all scenarios and replacing all non-turf landscaping with drought-resistant, low-water plants. The water required by the remaining turf is unchanged. The landscaping materials costs were assumed to be $27/m^2 for turf and $22/m^2 for non-turf plants. The EIO-LCA sector is "Greenhouse and nursery products." Xeriscaping is assumed to reduce water use by approximately 40 percent, a conservative assumption based on calculations (Gleick et al. 2003).

6.1.3.7 Water Pricing Options

This scenario analyzes the potential for reducing water use by changing the pricing of water by the utility. The analysis assumes outdoor water use will fall by 4 percent (Renwick and Archibald 1998). This reduction corresponds to a 10 percent price increase. Consumers are assumed to achieve the water reduction without additional investment in new plantings or irrigation systems, but only by minimizing over-watering. There are, therefore, no economic or external environmental costs associated with this scenario.

6.1.3.8 Dormant Turf

This scenario could also be called the "do nothing" scenario, literally. A minimal amount of outdoor water is used to maintain non-turf landscaping without any change in the landscape design. There are no economic costs or external environmental costs associated with this scenario. Water use is assumed to fall by 90 percent.

6.2 Task 6 Outcomes

The outcomes for demand management programs are described in this section.

6.2.1 Indoor Demand Management Results

Results are provided in terms of mass (kg) for air emissions and energy (MJ), as well as in economic terms ($). Table 31 presents the results for the NC-Current and NC-Proposed water supply. These results were determined as part of Task 5 but are presented for comparison to the conservation strategies. External costs were calculated by multiplying air emissions by cost estimates found in Table 22. Table 32 provides results for manufacturing water conserving fixtures needed to conserve one kl /d over 20 years. For water supply, it includes all infrastructure construction and energy use for the same volume of water and time frame.

Table 31: NC Supply Environmental and Economic Result Summary

Results per kl/d Supplied		NC-Current System	NC Marginal Supply[1]	Imported	Desal-inated	Recycled	Local Surface
Production Emissions	Energy (MJ)	3,900	11,000	5,500	15,000	6,600	3,300
	GHG (kg)	250	720	340	1,000	410	210
	NO_x (g)	580	920	610	1,300	550	570
	PM (g)	120	210	130	300	120	110
	SO_x (g)	850	2,200	1,100	3,100	1,200	750
	VOC (g)	180	410	210	570	250	160
	CO (g)	1,000	2,300	1,300	3,300	1,300	920
Lifecycle Cost ($)	Economic Cost-Purchase[2]	$6,400	$9,100	$7,400	$8,900	$11,000	$1,800
	External Environmental Costs	$140	$340	$170	$490	$190	$120
	Total Cost[3]	*$6,600*	*$9,400*	*$7,600*	*$9,400*	*$11,000*	*$1,900*

Notes:

[1] Marginal source is assumed to be an average of recycled and desalinated results. These combined sources are expected to supply the future needs of NC's customers. The marginal cost is assumed to be 90% of the average cost of these sources.

[2] System residential prices from (Renwick 2000); source-specific prices from (MWD 1996).

[3] Numbers may not sum due to rounding

Table 32: Environmental Effects of Indoor Residential Material Production

Model	Production Emissions per kl/day						
	Energy (GJ)	GHG (kg)	NO_x (g)	PM (g)	SO_x (g)	VOC (g)	CO (g)
TOILETS							
Toto Drake	28	2,000	3,300	530	3,300	2,200	19,000
Caroma Caravelle 305	22	1,500	2,600	410	2,500	1,700	15,000
Kohler Wellworth Pressure Lite	17	1,200	2,000	330	*2,000*	1,400	12,000
Niagara Ultimate	*7.0*	*490*	*830*	*130*	*820*	560	4,700
SHOWERHEADS							
Brasscraft LF	48	3,700	8,100	1,300	9,000	9,300	33,000
AM Conservation Spoiler	25	1,900	4,200	670	4,600	4,800	17,000
Niagara Earth	*11*	870	1,900	300	*2,100*	2,200	7,700
Niagara Earth Handheld	21	1,600	3,500	550	3,900	4,000	14,000
FAUCET							
Aerators							
New Resources Group	*1.3*	*100*	*200*	*54*	*260*	*120*	*790*
Niagara	*0.81*	*61*	*120*	*32*	*160*	*72*	*480*
Hands free devices							
Hands-free faucet controller	44	3,400	6,600	1,780	8,800	3,900	26,000
Delta e-Flow hands free	19	1,500	3,000	820	4,000	1,800	12,000
WASHING MACHINES							
Maytag Neptune	108	8,800	18,000	6,200	20,100	20,600	94,000
Frigidaire Gallery	33	2,600	5,500	1,870	6,100	6,200	28,000
Whirlpool Super Capacity+	90	7,300	15,000	5,180	16,800	17,200	79,000
Fisher & Paykel Ecosmart	106	8,700	18,000	6,110	19,800	20,300	93,000
Whirlpool Duet	61	5,000	10,000	3,520	11,400	11,700	53,000
Whirlpool Calypso	65	5,300	11,000	3,710	12,000	12,300	56,000

Note: Values shown in red italics are lower than results for NC's marginal supply.

In most cases, the environmental effects associated with producing the conserving fixtures are higher than the emissions associated with the current system supplying the water. The one exception is the SO_x emissions associated with the Niagara Ultimate toilet. The water conserving fixtures cause up to 35 times more GHG emissions than the NC-Current system. However, when the NC needs to provide water to meet future needs, they will not be able to get significantly more water from either importation or surface reservoirs. The marginal water source is likely a combination of recycled and/or desalinated water. The average emissions from these two sources were used to estimate the emissions for marginal water in the system. When the conserving fixtures were compared to the marginal source, the analysis indicates faucet aerators and the Niagara toilet are preferable to new supply for many chemicals. The pressure-assisted toilet and Niagara 6.6 lpm showerhead were preferable for SO_x.

However, these analyses only tell part of the story, the emissions caused by fixture manufacturing. Water conservation also has economic benefits of avoided water and energy purchases, as well as the avoided environmental emissions associated with them. These economic and environmental effects should all be considered in the final analysis. To assist this, the environmental emissions are translated into economic terms using external cost estimates. Four scenarios are considered: full production, early replacement (50 percent of production costs), marginal replacement, and end-of-life (no production costs). The last three scenarios assume that the fixture purchase is inevitable. If true, the early replacement scenario assumes only the effects above and beyond the inevitable should be included. In early replacement, the assumption is that the original fixture has exhausted half its service life and is being replaced by a more conserving fixture. For marginal replacement, the assumption is that only the price difference between the non-conserving and the conserving fixtures should be considered. The end-of-life scenario assumes that the original fixture is no longer usable and therefore no production costs should be considered as they are inevitable. The four scenarios analyzed bound the choices which a consumer may make. The results for the four scenarios in monetary units, including both economic and environmental external costs, are shown in Table 33.

The analysis shown in the table is from the consumer perspective, i.e., it represents the costs and savings to the household, as opposed to the costs and savings to the utility. The analysis does not include any rebates or other incentive programs which may lower the costs of the conservation to the consumer. Rebates or incentive programs may make more alternatives reasonable from the consumer perspective.

Table 33 shows that, when the emissions are translated to monetary costs and the economic costs for energy or water are included, the total full purchase costs are less than the marginal supply costs for all toilets, showerheads, the faucet aerators, and the Delta eFlow faucet. However, the full purchase scenario does not represent most consumer purchase decisions because it assumes that a consumer is choosing whether or not to purchase a fixture for the first time. In fact, the consumer is often replacing an existing fixture, either as an upgrade or to replace a broken fixture. The early replacement and end-of-life scenarios are more representative of this choice. Four of the six models of washing machines are also included under the early replacement scenario.

For washing machines and the Delta eFlow faucet, a marginal replacement scenario was also evaluated. This analysis compared the water-conserving device to a comparable non-conserving fixture from the same manufacturer. This scenario used the price difference between the models for the purchase costs and evaluated the external production costs based on the estimated differences in material inputs for the fixtures. Two washing machines are competitive in the marginal replacement scenario.

For the NC-Current supply system, external costs add two to six percent to the water price to capture costs of the air emissions included in the analysis. The conservation fixtures' external costs are one to four percent of the purchase price for the fixtures. These values capture only a portion of the external costs.

Table 33: Economic Impacts of Water Conservation

Lifecycle Costs ($) per kl/day Conserved/ Supplied		TOILETS				SHOWERHEADS				FAUCET				WASHING MACHINES					
										Aerators		Hands-free							
		Toto Drake	Caroma Caravelle 305	Kohler Wellworth Pressure Lite	Niagara Ultimate	Brasscraft LF	AM Conservation Spoiler	Niagara Earth	Niagara Earth Handheld	New Resources Group	Niagara	Hands-free faucet controller	Delta e-Flow hands free	Maytag Neptune	Frigidaire Gallery	Whirlpool Super Capacity+	Fisher & Paykel Ecosmart	Whirlpool Duet	Whirlpool Calypso
Economic Costs	Purchase	3,700	2,800	2,200	910	7,600	3,900	1,800	3,300	1,800	1,100	100,000	14,000	37,000	18,000	17,000	25,000	19,000	21,000
	Water[1]	-13	-65	-100	0	-84	-140	-240	-85	-80	-270	-39	-220	-310	-430	-410	-310	-590	-450
	Energy[2]	--	--	--	--	--	--	--	--	-1,000	-3,800	-490	-3,400	-1,300	-810	-820	-1,100	-770	-800
External Environmental Costs	Production	51	40	31	13	110	57	26	47	19	11	190	56	270	82	230	270	160	160
	Water Savings[3]	-10	-50	-77	0	-64	-100	-180	-65	-1.5	-5.1	-0.75	-4.2	-6.0	-8.3	-7.9	-5.9	-11	-8.7
	Energy Offset[4]	--	--	--	--	--	--	--	--	-38	-120	-16	-110	-71	-45	-46	-64	-43	-45
Total Costs	Full Purchase[5]	*3,700*	*2,800*	*2,100*	*920*	*7,600*	*3,800*	*1,400*	*3,200*	*610*	*-3,100*	100,000	9,900	36,000	17,000	16,000	23,000	17,000	20,000
	Early Replacement	*1,800*	*1,300*	*960*	*460*	*3,700*	*1,800*	*480*	*1,500*	*-280*	*-3,600*	52,000	*3,000*	17,000	*7,700*	*7,300*	11,000	*7,900*	9,500
	Marginal Replacement	--	--	--	--	--	--	--	--	--	--	--	*4,700*	17,000	*11,000*	*580*	*5,500*	*6,900*	9,400
	End-of-life Replacement	*-22*	*-110*	*-180*	*0*	*-150*	*-240*	*-430*	*-150*	*-1,200*	*-4,200*	*-540*	*-3,800*	*-1,700*	*-1,300*	*-1,300*	*-1,500*	*-1,400*	*-1,300*

Notes:

[1] Assumes water costs for EBMUD as reported in (Aquacraft 2005).

[2] Assumes residential consumer costs from a May 2007 Pacific Gas and Electric bill.

[3] Emissions are esimated based on NC's marginal supply.

[4] Emission factors are for the average California energy mix.

[5] *Italics* indicate results which are lower than the total costs of NC's marginal supply.

6.2.2 Indoor CII Demand Management Results

Table 34 summarizes both the material production environmental effects and the total economic costs associated with this scenario.

Table 34: Environmental Effects and Total Economic Cost Results for Office Building

Results per kl/d		Toilets		Urinals	
		Toilet 1	Toilet 2	Urinal 1	Urinal 2
Material Production	Energy (GJ)	41	83	590	1,000
	GHG (kg)	2,800	5,800	41,000	57,000
	NOx (g)	4,800	9,800	70,000	430,000
	PM (g)	770	1,600	11,000	370,000
	SOx (g)	4,800	9,700	69,000	440,000
	VOC (g)	3,200	6,600	47,000	460,000
	CO (g)	27,000	56,000	390,000	590,000
Economic costs	Purchase / installation costs	$8,500	$13,000	$110,000	$56,000
	Chemical costs				$2,500
	Water savings offset	-$350	-$350	-$350	-$350
External costs	Material production (fixtures, chemicals)	$75	$150	$1,100	$4,000
	Water savings offset	-$350	-$350	-$350	-$350
Total		$7,900	$13,000	$110,000	$62,000

Note: Numbers may not sum due to rounding

The total costs for all scenarios except Toilet 1 are higher than the costs associated with NC's marginal water supply (~$9,000). The results indicate the costs for replacing urinals are expensive given the water savings. Even the waterless urinal has high costs relative to the water savings. The total costs are approximately $7,000 less when the trap-seal liquid is not required. However, this amount is still not comparable to water supply. The potential water savings from toilets is much greater and more cost effective.

6.2.3 Outdoor demand management results

Table 35 presents the results for outdoor water saving strategies, including materials needed to conserve one kl/d over a period of 20 years compared to supplying water. For water supply, it includes all infrastructure construction and energy use for the same volume of water and time frame.

The results indicate that the material production external costs associated with outdoor strategies tend to exceed the external costs associated with NC's marginal supply as shown in Table 31. The smart controller (e.g., moisture sensor probes) alternative can be beneficial for certain emissions and energy use for large land users in dry climates of the inland and desert regions. In addition, rain runoff catchment and graywater reuse for large facilities is also preferable for a few environmental indicators in dry climates (i.e., energy use and SO_x).

Table 35: Environmental Impacts of Outdoor Water Conservation

Scenarios		Production Emissions per kl/day						
		Energy (GJ)	GHG (kg)	NO_x (g)	PM (g)	SO_x (g)	VOC (g)	CO (g)
Turf maintenance	SF1	130	11,000	17,000	3,000	11,000	9,600	47,000
	SF2	80	7,000	11,000	1,900	7,100	6,000	29,000
	SF3	57	5,000	7,500	1,300	5,100	4,200	21,000
	SF4	55	4,800	7,300	1,300	4,900	4,100	20,000
	MF	160	14,000	22,000	3,800	15,000	12,000	60,000
	COM	90	7,900	12,000	2,100	8,000	6,700	33,000
	IND	120	11,000	16,000	2,800	11,000	9,100	44,000
Drip Irrigation	SF1	560	42,000	87,000	12,000	94,000	90,000	370,000
	SF2	380	28,000	59,000	8,200	63,000	61,000	250,000
	SF3	290	22,000	45,000	6,300	49,000	47,000	190,000
	SF4	340	25,000	52,000	7,300	56,000	54,000	220,000
	MF	530	40,000	82,000	12,000	89,000	86,000	350,000
	COM	290	22,000	45,000	6,300	49,000	47,000	190,000
	IND	340	25,000	52,000	7,300	56,000	54,000	220,000
Moisture sensor probes	SF1	61	4,900	9,900	3,400	17,000	6,400	45,000
	SF2	32	2,500	5,100	1,800	8,800	3,300	23,000
	SF3	19	1,500	3,000	1,000	5,200	2,000	14,000
	SF4	*7*	*600*	1,200	400	*2,000*	750	5,300
	MF	99	7,900	16,000	5,500	28,000	10,000	73,000
	COM	*6*	*500*	1,000	350	*1,700*	660	4,600
	IND	*7*	*600*	1,200	420	*2,100*	780	5,500
Rain barrel catchment	SF1	110	8,300	18,000	2,900	20,000	21,000	73,900
	SF2	160	13,000	27,000	4,400	31,000	32,000	110,000
	SF3	590	46,000	100,000	16,000	110,000	110,000	410,000
	SF4	66	5,700	19,000	4,200	16,000	16,000	59,000
	MF	85	6,500	14,000	2,300	16,000	16,000	58,000
	COM	*8*	*700*	2,400	530	*2,000*	2,000	7,500
	IND	*10*	900	2,900	650	2,500	2,400	9,100
Greywater	SF1	240	18,000	35,000	5,100	40,000	32,000	130,000
	SF2	200	15,000	30,000	4,400	34,000	28,000	110,000
	SF3	190	14,000	27,000	4,000	31,000	25,000	110,000
	SF4	260	19,000	38,000	5,700	44,000	36,000	150,000
	MF	480	35,000	65,000	9,800	79,000	53,000	220,000
	COM	97	7,100	13,000	2,000	16,000	9,700	42,000
	IND	13	900	1,800	280	*2,200*	1,500	6,500
Xeriscaping	SF1	80	7,600	21,000	13,000	17,000	15,000	120,000
	SF2	55	5,200	14,000	9,200	12,000	10,000	80,000
	SF3	43	4,100	11,000	7,200	9,400	8,100	63,000
	SF4	51	4,900	13,000	8,600	11,000	9,600	75,000
	MF	70	6,700	18,000	12,000	15,000	13,000	100,000
	COM	38	3,700	10,000	6,500	8,400	7,200	56,000
	IND	46	4,400	12,000	7,800	10,000	8,700	68,000

Note: Italics indicates results lower than NC marginal supply's energy use and air emissions.

Table 36 presents the results in terms of economic and external environmental costs. In contrast to the residential water fixtures discussed in the previous section, only the full purchase costs are listed. The "early replacement" and "end-of-life" scenarios are only relevant when an existing system is being replaced, generally not the case for the landscaping and irrigation systems included in this assessment.

All alternatives except drip irrigation are preferable to water supply under this assessment under at least two scenarios. Because drip irrigation only reduces water use in the non-turf areas, it requires significant investment (in economic and material terms) without affecting all irrigation use. The relationship between water use and system cost is assumed to be linear. Economies-of-scale could make drip irrigation more beneficial for larger facilities.

Turf maintenance and xeriscaping are preferable to supply for all scenarios. The costs for turf maintenance are several thousand dollars lower than replacing all the landscaping. If the landscaping plants are assumed to last twice as long, the costs for turf maintenance and xeriscaping are similar. In addition, the authors suspect that the savings estimate for xeriscaping from (Gleick et al. 2003) is conservative. They estimate savings of 40 percent but using the assumptions associated with these scenarios the savings were calculated to be 42 to 53 percent depending on the scenario.

Generally speaking, costs for smart controllers were lower than supply costs when larger, drier yards were in the scenario. Smart controllers were not preferred for the cooler, wetter San Francisco coastal climate or for the small yard associated with the Los Angeles apartment building. Rain runoff catchment is seen to be preferred in the wetter Northern California climate and for larger buildings where roofs can collect more water (multi-family, ranchette, commercial, and industrial buildings). Graywater is only preferred for large facilities with large production of reusable water (the COM and IND scenarios).

The results for the dormant turf and water pricing alternatives are not shown in Tables 35 and 36 because the cost savings per kl /d water savings are equal to the economic cost of the water for all scenarios (-$7,100). However, the savings per facility varies for these alternatives. Table 36 shows the water savings for certain alternatives, including water pricing and dormant turf.

Table 36: Environmental Effects of Outdoor System Material Production

Scenario		System Life-cycle Costs for kL/day over 20 years				
		Economic Costs		External Environmental Costs		
		Purchase	Water	Production	Water Offset	Full Costs
Turf maintenance	SF1	$5,900	-$7,100	$270	-$340	*-$1,200*
	SF2	$3,700	-$7,100	$170	-$340	*-$3,600*
	SF3	$2,600	-$7,100	$120	-$340	*-$4,700*
	SF4	$2,500	-$7,100	$120	-$340	*-$4,800*
	MF	$7,500	-$7,100	$350	-$340	*$440*
	COM	$4,100	-$7,100	$110	-$340	*-$3,200*
	IND	$5,600	-$7,100	$150	-$340	*-$1,700*
Drip Irrigation	SF1	$64,000	-$7,100	$810	-$340	$58,000
	SF2	$43,000	-$7,100	$550	-$340	$36,000
	SF3	$33,000	-$7,100	$420	-$340	$26,000
	SF4	$38,000	-$7,100	$490	-$340	$32,000
	MF	$25,000	-$7,100	$770	-$340	$18,000
	COM	$61,000	-$7,100	$420	-$340	$54,000
	IND	$33,000	-$7,100	$490	-$340	$26,000
Moisture sensor probes	SF1	$18,000	-$7,100	$170	-$340	$11,000
	SF2	$9,300	-$7,100	$90	-$340	*$2,000*
	SF3	$5,500	-$7,100	$50	-$340	*-$1,900*
	SF4	$2,100	-$7,100	$20	-$340	*-$5,300*
	MF	$29,000	-$7,100	$270	-$340	$22,000
	COM	$1,800	-$7,100	$20	-$340	*-$5,600*
	IND	$2,200	-$7,100	$20	-$340	*-$5,200*
Rain barrel catchment	SF1	$17,000	-$7,100	$280	-$340	*$10,000*
	SF2	$26,000	-$7,100	$420	-$340	$19,000
	SF3	$94,000	-$7,100	$1,500	-$340	$88,000
	SF4	$4,600	-$7,100	$230	-$340	*-$2,600*
	MF	$13,000	-$7,100	$220	-$340	*$6,200*
	COM	$600	-$7,100	$30	-$340	*-$6,800*
	IND	$700	-$7,100	$30	-$340	*-$6,700*
Greywater	SF1	$27,000	-$7,100	$550	-$340	$21,000
	SF2	$23,000	-$7,100	$470	-$340	$16,000
	SF3	$21,000	-$7,100	$430	-$340	$14,000
	SF4	$30,000	-$7,100	$600	-$340	$23,000
	MF	$53,000	-$7,100	$1,000	-$340	$47,000
	COM	$11,000	-$7,100	$200	-$340	$3,400
	IND	$1,500	-$7,100	$30	-$340	-$5,900
Xeriscaping	SF1	$17,000	-$7,100	$320	-$340	*$9,400*
	SF2	$11,000	-$7,100	$220	-$340	*$4,100*
	SF3	$8,900	-$7,100	$170	-$340	*$1,600*
	SF4	$11,000	-$7,100	$200	-$340	*$3,300*
	MF	$14,000	-$7,100	$280	-$340	*$7,300*
	COM	$7,900	-$7,100	$150	-$340	*$700*
	IND	$9,500	-$7,100	$180	-$340	*$2,300*

Note: Water source is NC's marginal supply. Italics indicates results which are lower than the cost of NC's marginal supply.

Table 37 shows that options which do not require economic and environmental investments generally create the lowest total costs. Supplying the marginal water saved in the water pricing alternative would range from under $100 to over $5000, while for the dormant turf alternative the costs would range from approximately $1500 to $80,000. This shows that avoiding water use without technological change provides the greatest benefit. Depending on the plants used in the yard, the dormant turf option may not be aesthetically pleasing for consumers and, therefore, is less likely to be adopted.

Table 37: Household/Facility Economic Impacts of Outdoor Water Conservation

Scenario		Household/Facility System Life-cycle Costs over 20 years				
		Economic Costs		External Environmental Costs		
		Purchase	Water	Production	Water Offset	Full Costs
Turf maintenance	SF1	$340	-$400	$16	-$20	-$71
	SF2	$400	-$780	$19	-$38	-$390
	SF3	$490	-$1,330	$23	-$65	-$880
	SF4	$2,100	-$6,000	$99	-$300	-$4,100
	MF	$130	-$120	$6	-$6	$8
	COM	$5,800	-$9,900	$160	-$480	-$4,500
	IND	$5,200	-$6,600	$150	-$320	-$1,600
Xeriscaping	SF1	$3,700	-$1,600	$70	-$77	$2,100
	SF2	$4,900	-$3,000	$94	-$150	$1,800
	SF3	$6,500	-$5,200	$120	-$250	$1,200
	SF4	$35,000	-$24,000	$680	-$1,200	$11,000
	MF	$1,000	-$490	$19	-$24	$510
	COM	$43,000	-$39,000	$830	-$1,900	$3,700
	IND	$35,000	-$26,000	$670	-$1,300	$8,600
Water Pricing	SF1	$0	-$160	$0	-$8	-$160
	SF2	$0	-$300	$0	-$15	-$320
	SF3	$0	-$520	$0	-$25	-$540
	SF4	$0	-$2,400	$0	-$120	-$2,500
	MF	$0	-$50	$0	-$2	-$51
	COM	$0	-$3,900	$0	-$190	-$4,000
	IND	$0	-$2,600	$0	-$130	-$2,700
Dormant Turf	SF1	$0	-$3,620	$0	-$180	-$3,800
	SF2	$0	-$7,000	$0	-$340	-$7,300
	SF3	$0	-$11,950	$0	-$580	-$12,530
	SF4	$0	-$54,350	$0	-$2,700	-$57,002
	MF	$0	-$1,100	$0	-$55	-$1,200
	COM	$0	-$88,960	$0	-$4,300	-$93,307
	IND	$0	-$59,710	$0	-$2,900	-$62,631

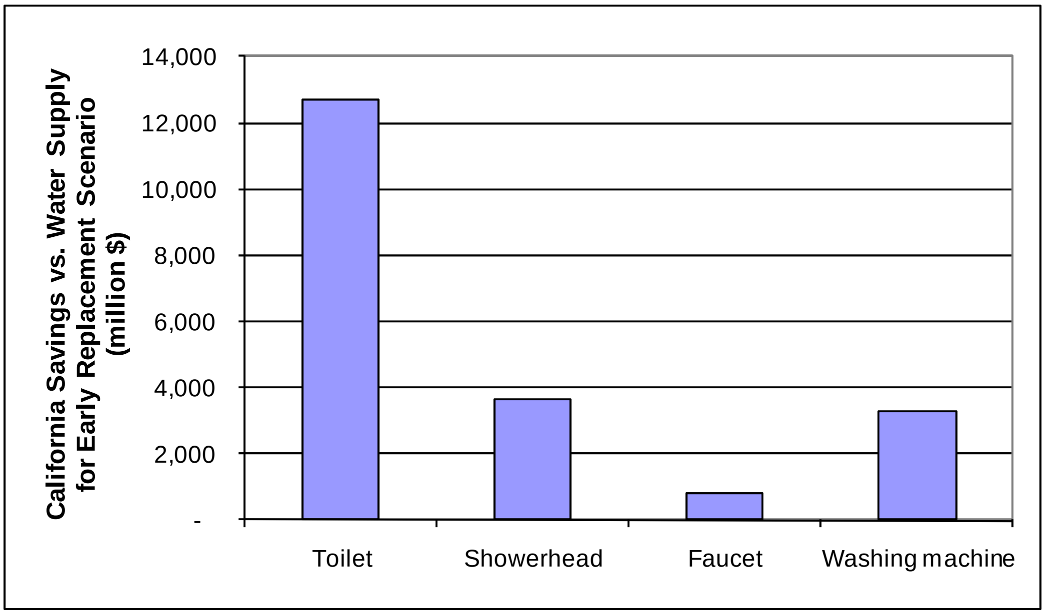
However, it should be noted that the results are sensitive to a number of factors, including yard size, irrigated area, turf area, plant types, topography (i.e., some scenarios could require pumping which was not included in the analysis), building size, material and water costs, etc. These results should only be taken as guidelines and not as absolute results.

6.3 Task 6 Conclusions and Recommendations

6.3.1 Indoor Demand Management Conclusions

The indoor residential demand management analysis indicates that investing in indoor residential demand management is environmentally preferable to supplying water. The Pacific Institute study indicates there is still great potential for reducing water demand by these methods (Gleick et al. 2003). Figure 17 shows the statewide potential economic savings (including external costs) for the early replacement scenario.

Figure 17: Potential Savings Statewide of Indoor Demand Management Fixtures



The analysis uses Pacific Institute's estimates for conservation potential of toilets, showerheads, and washing machines (Table 23) and assumes installation of the most inexpensive fixture in the early replacement scenario. The results assume there are one million households in California and that low-flow faucets have a 50 percent market penetration. The costs of conservation are compared to the costs of NC's marginal supply. However, for washing machines, the analysis also indicates that some models are priced too high for costs to be recouped under many purchase scenarios even when water and energy savings are considered. Manufacturers should consider these outcomes when pricing their models.

There are a number of limitations to the outcome of this study. First, the results should not be taken as representative for these models under all circumstances. The original Aquacraft studies were of a limited scope, in terms of numbers of households studied and geography. Since the outcomes for each fixture are tied to the Aquacraft results, they can be taken as indicative, but not absolute, comparisons. In addition, the households chosen for the Aquacraft study had above-average water use and, therefore, had greater potential for water savings than the average household. This factor likely overestimates the water savings from replacing indoor household fixtures in an average or below average water-consuming home. Second, an uncertainty assessment was not conducted on the results. In reality, the economic estimates of price and external costs could cover a wide range but in this study are reduced to a single number. It is an indicative value but cannot be used as an absolute outcome.

6.3.2 Indoor CII Demand Management Conclusions

In the assumed scenario, the cost of conservation should be evaluated for the particular office building. The results shown in Table 29 are sensitive to the number of flushes per day, either on because the per capita flushes or number of employees are not accurate. The result that waterless urinals do not provide significant savings relative to existing urinals was surprising. If the waterless urinal is compared to a pre-1994 toilet the total costs are more favorable and comparable to the Toilet 2 results but are still not competitive with the assumptions made for the NC's marginal supply.

6.3.3 Outdoor Demand Management Conclusions

The analysis of outdoor demand management indicates that many, but not all, alternatives are beneficial when compared to supplying the marginal water source using a life-cycle perspective. Four alternatives (turf maintenance, xeriscaping, water pricing, and dormant turf) led to lower costs to consumers under all scenarios. These alternatives should be encouraged to reduce overall water use.

The analysis included in this paper implicitly assumes that these alternatives are mutually exclusive. However, some can be used in conjunction with others. While the water savings will generally increase as different strategies are employed, the water savings associated with different alternatives should not be assumed to be strictly additive.

In addition, for some scenarios there may be economic and environmental savings associated with reduced energy or chemical use. Xeriscaped yards, for example, do not require fertilizers or mowing as much as some other landscapes do. Data was not available about the frequency of feeding and mowing. Therefore, reliable estimates of these savings were impossible. However, for a comprehensive assessment, this should be considered when comparing outdoor water alternatives

CHAPTER 7:
Task 7 – Consider Additional Pollutants

WEST and WWEST were revised to include additional pollutants in the assessment. The Phase One version of WEST assessed the emissions of greenhouse gases and the resulting GHG, NO_x, SO_x, PM, VOC, and CO. To improve the results, various air and water toxic releases caused by production of materials and energy were also included. These results give a more comprehensive picture of the environmental effects caused by water systems.

7.1 Task 7 Approach

Task 7 consisted of collecting the EF data needed to revise the tool, updating the necessary calculations and documentation, and analyzing a hypothetical case study of the use of desalinated water in California.

7.1.1 Revisions

Both tools, WEST and WWEST, were updated to include additional pollutants to land, air, and water due to material and fuel production. The emissions to land are reported as a single volume (in kg). For air and water, emissions for specific chemicals are reported in kg. Two EF sources were used to obtain additional pollutant data, EIO-LCA and the commercially-available LCA software, GaBi (CMU 2007; GaBi 2003). Air and water pollutants with EFs in both EIO-LCA and GaBi were included in the analysis. Emissions to land were only available in EIO-LCA. Tables 38 and 39 summarize the chemical air and water pollutants, respectively. All pollutants listed can now be analyzed in both WEST and WWEST.

Because the average user may not be interested in results for all chemicals, the original results pages in WEST and WWEST were left unchanged. If a user wants more detailed emissions to air and water, they can reference two new worksheets in each tool, “Results-ALL AIR” and “Results-ALL WATER”. Results are presented in tabular form. All EFs can be found in the new tabs: “final water efs” and “final air efs”. The calculations are similar to those described previously for assessing material production for both tools and can be generally described by Equation 7-1 for EIO-LCA and Equation 7-2 for GaBi.

Equation 7-1: $$MPEmission = \frac{EIOLCAEF * UnitCost * Units\# * FunctionalUnit}{AnalysisPeriod * VolumeTreated}$$

Equation 7-2: $$MPEmission = \frac{GabiEF * UnitWeight * Units\# * FunctionalUnit}{AnalysisPeriod * VolumeTreated}$$

Table 38: Air Emission Factors added to WEST and WWEST

AIR EMISSIONS	
1,1,1-TRICHLOROETHANE	DICHLORO-
1,1-DICHLORO-	TETRAFLUOROETHANE
1-FLUOROETHANE	DIOXIN AND DIOXIN-LIKE
1,2,4-TRIMETHYLBENZENE	COMPOUNDS
1,2-DIBROMOETHANE	ETHYLBENZENE
1-CHLORO-1,1-	ETHYLENE
DIFLUOROETHANE	FLUORINE
ACETALDEHYDE	FORMALDEHYDE
ACROLEIN	HYDROCHLORIC ACID
ACRYLONITRILE	HYDROGEN CYANIDE
AMMONIA	HYDROGEN FLUORIDE
ANTHRACENE	LEAD
ANTIMONY	LEAD COMPOUNDS
ARSENIC	MANGANESE
ARSENIC COMPOUNDS	MERCURY
BARIUM	METHANOL
BENZENE	NAPHTHALENE
BENZO(G,H,I)PERYLENE	NICKEL
BERYLLIUM	PHENANTHRENE
BROMINE	PHENOL
CADMIUM	POLYCHLORINATED BIPHENYLS
CARBON DISULFIDE	POLYCYCLIC AROMATIC
CARBON TETRACHLORIDE	COMPOUNDS
CHLORINE	PROPYLENE
CHLORODIFLUOROMETHANE	SELENIUM
CHLOROTRIFLUOROMETHANE	SILVER
CHROMIUM	STYRENE
CHROMIUM COMPOUNDS	THALLIUM
COBALT	TOLUENE
COPPER	TRICHLOROFLUOROMETHANE
CUMENE	VANADIUM
CYCLOHEXANE	VINYL CHLORIDE
DICHLORODIFLUOROMETHANE	XYLENE
DICHLOROMETHANE	ZINC

Table 39: Water Emission Factors Added to WEST and WWEST

WATER EMISSIONS	
1,2-DIBROMOETHANE	FLUORINE
1,2-DICHLOROETHANE	HYDROGEN FLUORIDE
1,2-DICHLOROPROPANE	LEAD
ACRYLONITRILE	MANGANESE COMPOUNDS
ALUMINUM	MERCURY
AMMONIA	METHANOL
ANTHRACENE	NAPHTHALENE
ANTIMONY	NICKEL
ARSENIC	NITRATE COMPOUNDS
BARIUM	PHENOL
BENZENE	PHOSPHORUS
BERYLLIUM	POLYCYCLIC AROMATIC
BROMINE	COMPOUNDS
CADMIUM	SELENIUM
CHLORINE	SILVER
CHLOROMETHANE	SULFURIC ACID
CHROMIUM	THALLIUM
CHROMIUM COMPOUNDS	TOLUENE
COBALT	VANADIUM
COPPER	VINYL CHLORIDE
CYANIDE COMPOUNDS	XYLENE
ETHYLBENZENE	ZINC

7.1.2 Case Study

The updated WEST was used to analyze the environmental effects of using desalination to provide water to coastal California. Prior data from a seawater desalination system was entered into the revised tool and used to estimate the production of water needed to supply several of California's largest coastal cities: San Diego, Los Angeles, and San Francisco. These results are not intended to be a realistic assessment of the future of water supply in California but may be considered a worst-case scenario.

The total water volumes needed to supply each of these cities, along with the associated utility, are listed in Table 40. The data were obtained from utility websites. The total water volume analyzed, 1,500,000 Ml/yr, represents approximately 15 percent of California's urban water supply in the year 2000 (DWR 2005).

Table 40: Water Production for Three Cities

City	Utility	Annual Potable Water Production (Ml)
San Diego	San Diego Water Department	300,000
Los Angeles	Los Angeles Department of Water and Power	830,000
San Francisco	San Francisco Public Utility Commission	410,000
TOTAL		*1,540,000*

The desalination systems used to supply the water are assumed to take water from the Pacific Ocean. The plants will be more energy and material intensive than previously-analyzed desalination systems because the salinity in the ocean is higher than the desalination sources in other case studies, brackish groundwater and San Francisco bay water. Salinity is proportional to the need for electricity and maintenance of the treatment process. Only emissions associated with treatment are included since the supply and distribution design and operation parameters will be site-specific for any plants which may be built in these cities. The case study will be referred to as "Desal".

All desalination plants used to provide potable water to these cities will be similarly designed with membrane filtration pre-treatment, RO membrane treatment, and disinfection with sodium hypochlorite. The increased salinity of this system will increase the electricity use by a factor of 65 percent over a brackish groundwater system in the SC case study. Details of chemical and electricity consumption for the Desal case study are shown in Table 41.

Table 41: Ocean Desalination Case Study Details

Chemical consumption (kg/Ml)	
Sulfuric acid	81
Aqueous ammonia	8.4
Calcium carbonate	26
Carbon dioxide	26
Sodium hypochlorite	6.5
Other	7.5
Electricity consumption (MWh/Ml)	4.0

Note: "Other" includes chemicals with consumption <5 kg/Ml (ferric chloride, scale inhibitor, zinc orthophosphate, and fluoridation and membrane cleaning chemicals)

7.2 Task 7 Outcomes

The revisions to WEST were tested by analyzing a hypothetical scenario for providing desalinated water to Coastal California. Table 42 shows the results for this case study per Ml and also for providing all the water to three cities: San Diego, Los Angeles, and San Francisco.

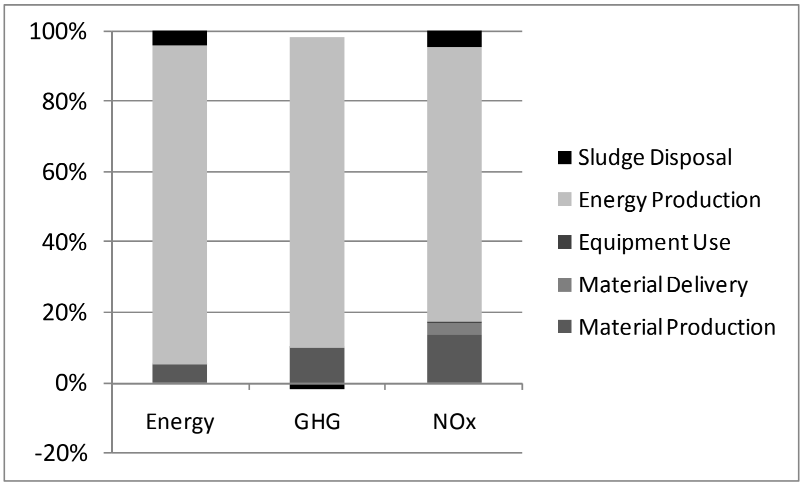
Table 42: Desalination Energy and Air Emission Results

Effect	Results per Ml	Results for Three Cities (x1,000,000)
Energy (GJ)	49	75
GHG (kg)	2,239	3,448
NOx (g)	1,871	2,882
PM (g)	642	989
SOx (g)	7,182	11,060
VOC (g)	1,348	2,076
CO (g)	2,365	3,642

The operational phase dominates the results for all environmental effects, primarily due to electricity consumption. Operating the system is responsible for more than 90 percent of GHG emissions. The GHG emissions associated with supplying San Diego, Los Angeles, and San Francisco, or 15 percent of the state's urban water supply, corresponds to 3 percent of the GHG estimates for statewide energy production (CEC 2008).

Figure 18 shows the breakdown of energy, GHG, and NO_x results for each activity and verifies that energy production is the most significant contributor. Material production is also important, contributing more than 10 percent to both GHG and NO_x. The other activities, material delivery, equipment use, and sludge disposal, are less important (<5 percent of overall results). The emissions from sludge disposal from this plant are negative because the assumed landfill is able to capture and flare 90 percent of the methane (CH_4) produced. The effect is small (-2 percent of overall results) but is the only source of emission savings found in the analysis.

Figure 18: Desalination Results by Activity



Tables 43 and 44 list the expanded emissions added as part of Task 7. Table 43 shows land and air emissions. Table 44 summarizes emissions to water. Emissions which are less than 0.1 g/Ml are not shown in either table. Expanded emissions are due solely to material production. WEST does not contain EFs for these chemicals for other activities, including energy production. The emissions associated with these other activities may be significant.

Table 43: Expanded Land and Air Emissions Results

Chemical	Emission (g/Ml)	Chemical	Emission (g/Ml)
Land Releases	82	CFC-114	0.062
1,1,1-Trichloroethane	0.059	Ethylbenzene	0.10
1,1-Dichloro-1-fluoroethane	0.10	Ethylene	1.3
1,2,4-Trimethylbenzene	0.013	Formaldehyde	0.21
1,2-Dibromoethane	0.022	Hydrochloric acid	3.4
1-Chloro-1,1-difluoroethane	0.048	Hydrogen cyanide	0.29
Acetaldehyde	0.059	Hydrogen fluoride	0.31
Acrylonitrile	0.018	Methanol	0.78
Ammonia	1.8	Naphthalene	0.021
Barium	0.098	Nickel	0.020
Benzene	0.28	Phenol	0.032
Bromine	0.027	Polycyclic aromatic compounds	0.076
Carbon disulfide	0.64	Propylene	0.47
Carbon tetrachloride	0.027	Styrene	0.10
Chlorine	0.33	Toluene	0.36
Chlorodifluoromethane	0.36	Trichlorofluoromethane	0.012
Cumene	0.044	Vanadium	0.090
Cyclohexane	0.16	Vinyl chloride	0.039
Dichlorodifluoromethane	0.034	Xylene	0.40
Dichloromethane	0.15	Zinc	0.024

Note: Only chemicals with emissions > 0.01 g/Ml are shown.

Table 44: Water Emissions Results

Chemical	Emission (g/Ml)	Chemical	Emission (g/Ml)
Aluminum	1.6	Methanol	56
Ammonia	0.25	Nickel	0.017
Arsenic	0.011	Nitrate compounds	5.8
Barium	0.34	Phenol	0.097
Benzene	0.046	Phosphorus	0.018
Chlorine	0.37	Sulfuric acid	0.54
Chromium	0.029	Toluene	0.029
Copper	0.027	Xylene	0.026
Lead	0.019	Zinc	0.11
Manganese compounds	0.091		

Note: Only chemicals with emissions > 0.01 g/Ml are shown.

7.3 Task 7 Conclusions and Recommendations

7.3.1 Revisions

The addition of land, water, and additional air emission results to WEST and WWEST will improve the functionality of the tools for users. The improvement will be most interesting to those who are interested in very specific emissions that can be important to their local environment.

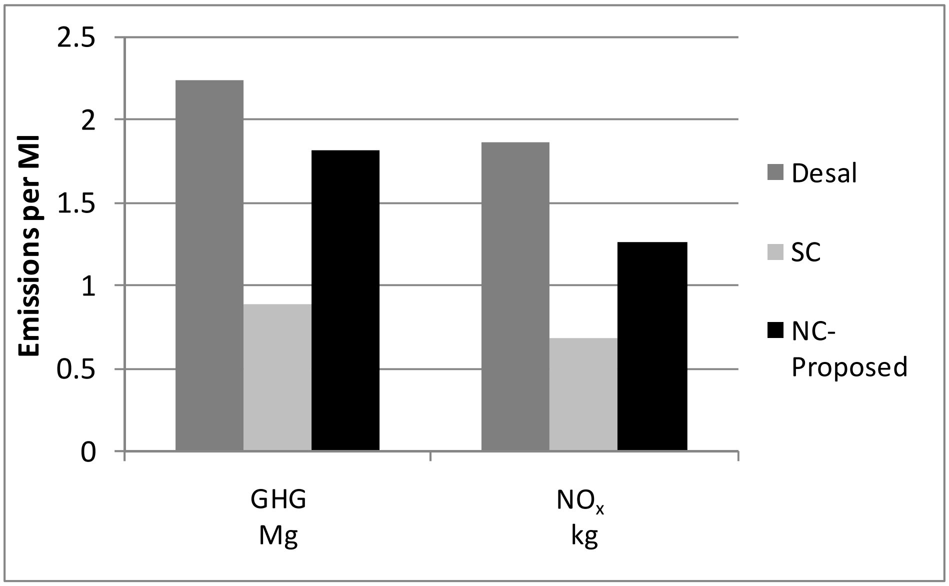
A potential future improvement to the tool would be to place these results into a more meaningful context. For instance, they could be normalized by their expected toxicity or effect on water quality. Instead of seeing a chemical-by-chemical list, the results would be contextualized to a more meaningful outcome for users.

7.3.2 Case Study

The Desal case study provides important bounds on the results for potential desalination scenarios in California. Several urban utilities are considering or implementing desalination plants for back-up or emergency water supply. The reliability concerns driving these decisions cannot be ignored and may necessitate the use of desalinated water. However, this analysis provides insight into the potential impact on the state's energy supplies, also a limited resource, if this trend continues unabated.

Figure 19 compares the treatment results from the Desal case study with previously-analyzed desalination systems. The effects of supply and distribution have not been included as they will vary depending on local conditions. The figure shows results from the SC case study (brackish groundwater) and the NC-Proposed case study (less saline bay water) and illustrates a range of outcomes for different desalination scenarios available in the state of California. As expected, the results for seawater desalination are consistently higher than the other two designs. In the case of brackish groundwater, the difference is more than a factor of two.

Figure 19: Desalination Results Comparison



These results can better inform utilities that are comparing different potential sources of desalinated water. Further comparisons of these and other case studies can be found in Chapter 12.

CHAPTER 8: Task 8 – Develop Workshops for Industry Professionals

Two workshops for California water professionals were developed to introduce the capabilities of WEST to potential users. The workshops educated the industry about the issues and limitations associated with assessing the life-cycle environmental effects of infrastructure and encouraged dialogue between researchers and practitioners in this area.

8.1 Task 8 Approach

Two workshops were held, one in Northern California and one in Southern California. To minimize economic and environmental travel costs, the Northern California workshop was webcast to allow parties in other areas of the state to participate. Workshops were advertised through the California Energy Commission, the Berkeley Water Center, the Association of California Water Agencies, local American Water Works Association chapters, the California Water Environment Association, and other means.

8.2 Task 8 Outcomes

The Northern California Workshop was held on December 8, 2009 on the University of California, Berkeley campus. The workshop was well attended. Forty-three people attended in person, representing nine different utilities, five government agencies, twelve consulting firms, and six other organizations. The workshop was also webcast. At least an additional 26 people attended via the webcast (the final number was difficult to establish). Workshop feedback forms were completed by 17 of the attendees. The feedback was useful, constructive and uniformly positive, and many suggestions were incorporated into the Southern California workshop.

A second workshop was held in Southern California on February 1, 2010 at the Orange County Water District in Fountain Valley. Seventeen people attended, representing six different utilities and three consulting firms. Copies of the slides for the Northern and Southern California workshops can be found in Appendices G.1 and G.2, respectively.

Each session was scheduled for 3 hours. The Northern California session prompted many questions and ran an additional 45 minutes. The workshop presented the general LCA methodology and attendees discussed what would be considered when completing a simple LCA analysis. Participants were also introduced to the capabilities of WEST and WWEST as well as the data required for an analysis. The researchers presented results from prior case studies and discussed how these may be improved in future analyses. A question and answer period followed the formal talk. After the workshop, participants provided feedback about how they would enhance the capabilities of the tools. Participants will be invited to participate in future research as case study systems.

8.3 Task 8 Conclusions and Recommendations

The workshops were well-attended and demonstrate that the water and wastewater industry is interested in issues of sustainability, energy efficiency, and greenhouse gas emissions. These researchers, and the Energy Commission, should try to keep the participants, and other interested parties, apprised of the latest research and tools available for evaluating these issues after this contract ends.

CHAPTER 9:
Task 9 – Improve Material Production Analysis

In Task 9, the authors updated WEST to improve the analysis of material production and analyzed two case study systems using the updated tool.

9.1 Task 9 Approach

9.1.1 Revisions

After Phase One, environmental emissions from material production were estimated solely using EIO-LCA with appropriate, but aggregated, economic sectors. In many cases, these sectors assessed emissions well (e.g., ready-mixed concrete is produced all over the nation using similar process to produce a consistent product). However, other sectors include a variety of products which consist of different raw materials and using an array of manufacturing processes. Task 9 was intended to incorporate process-based LCA techniques (e.g., GaBi [GaBi 2005]) to create more specific results for sectors which include diverse products. For example, process-based LCA improves the analysis of different chemicals used in the treatment system.

Other revisions were completed on both WEST and WWEST are summarized below:

- Inserted new EFs for fuel production from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (USDOE 2009);
- Edited fuel production calculations to include alternative fuels in both tools;
- Updated Material Delivery calculations to incorporate new EFs from (Facanha and Horvath 2007);
- Added passenger transit modes EFs from (Chester 2008); and
- Updated electricity EFs with 2005 state data from E-GRID (USEPA 2007).

9.1.2 Case Studies

To demonstrate the capabilities of the revised WEST, two case studies were analyzed. The prior utilities analyzed served populations of approximately 200,000 people. The new case studies were selected such that one was significantly larger and one significantly smaller. In addition, the small case study uses a water source never previously analyzed, local groundwater.

9.1.2.1 Large Utility

The authors selected a utility in Northern California (NC-Large) which serves over one million people and supplies over 250 billion liters of water per year. The utility asked not to be specifically identified. Data were obtained through utility reports, web page, and communications with staff. The details of this case study were previously published in (Stokes and Horvath 2011) and are summarized below with some revisions.

Approximately 90 percent of NC-Large's water supply is imported through aqueducts from a surface water source located 150 kilometers (km) inland. Eight percent of the imported water (7 percent of tall water) is stored in reservoirs prior to use. The remainder of the utility's potable supply is collected in local reservoirs. All water is treated conventionally, though the stored and reservoir water require more extensive treatment than water that is imported and used directly. Treated water is distributed within the service area. Table 45 provides case study details. Sludge disposal information was not provided by the utility; data from published case studies were scaled to analyze sludge disposal effects (Stokes and Horvath 2009). Sludge was assumed to be landfilled 50 km away. The landfill flares 85 percent of the CH_4 produced.

Table 45: NC-Large Case Study Summary

	IMPORTED[1]			RESERVOIR	
	Supply	**Treatment**	**Distribution**	**Supply**	**Treatment**
Pipelines (km)	470	NA	6,510	NA	NA
Steel/DI pipe (%)	96%	NA	63%	NA	NA
Concrete/AC pipe (%)	4%	NA	28%	NA	NA
PVC pipe (%)	--	NA	8%	NA	NA
Pumps (#)	29	20	380	NA	
Pump stations (#)	7	--	130	NA	--
Reservoirs/tanks (#)	7	--	170	NA	--
Electricity (MWh/yr)[2]	2,300	7,200	61,000	30,000	5,700
Natural gas (MBTU/yr)[2]	28,000	11,000	21,000	670	7200
Chemicals (liter/yr)[2]					
Ammonia	--	790,000	--	--	140,000
Polymer	--	290,000	--	--	43,000
Caustic soda	--	840,000	--	--	450,000
Hydrofluosilicic acid	--	910,000	--	--	120,000
Sodium hypochlorite	--	4,700,000	--	--	1,100,000
Polyaluminum chloride	--	530,000	--	--	--
Sodium bisulfite	--	200,000	--	--	--
Alum	--	--	--	--	1,200,000
Fleet and equipment use[3]					
Heavy-duty truck (miles/yr)			460,000		--
Light-duty truck (miles/yr)			4,500,000		--
Hybrid automobile (miles/yr)			350,000		--
Construction equipment (hours/yr)			15,000		--

Notes: NA = Not available. DI = Ductile iron. AC = Asbestos cement.

[1] The majority of water (95%) in the system is imported. However, 8% of imported water (7% of total) is stored in reservoirs until needed. The stored water is analyzed using the imported supply data and the reservoir treatment data. The same distribution is used for all water sources. The effects of construction and operation are distributed proportionally between all water sources the three sources. The stored supply infrastructure is also used for reservoir water.

[2] Year 2008 electricity, natural gas, & chemical consumption; electricity (6,600 MWh) & natural gas (32,000 MBTU) consumed for miscellaneous activities were distributed between the supply, treatment, and distribution systems.

[3] Fleet data based on year 2007 use; fleet use was distributed between the supply, treatment, and distribution systems for this analysis.

9.1.2.2 Small Utility

A second Northern California utility (NC-Small) was also evaluated to demonstrate WEST's usefulness for small systems. This utility serves approximately 50,000 customers and supplies almost 6.7 billion liters of water annually. The utility asked not to be specifically identified. Data were obtained through utility reports, web page, and communications with staff.

Local groundwater aquifers supply NC-Small's water. The supply system consists of 18 production and a similar number of monitoring wells. The water from ten of those wells, about half of the total volume, comes from a pure source and requires only disinfection. The remainder is treated at the individual eight wellheads, using coagulation, filtration, activated carbon, chemical addition to remove iron and manganese, and/or disinfection. Treated water is distributed within the service area. Table 46 provides case study details. Sludge disposal information was not provided by the utility and was not included in the analysis.

Table 46: NC-Small Case Study Summary

		TREATMENT		
	SUPPLY	Full Treatment	Disinfection only	DISTRIBUTION
Pipelines (km)	--	NA	NA	260
Steel/DI pipe (%)	--	NA	NA	7%
Concrete/AC pipe (%)	--	NA	NA	59%
PVC/PE pipe (%)	--	NA	NA	34%
Production Wells (#)	18	--	--	--
Pumps (#)	17	--	--	28
Pump stations (#)	--	--	--	10
Reservoirs/tanks (#)	--	--	--	19
Electricity (MWh/yr)[1]	2,500	88	--	735
Chemicals (liter/yr)[1]				
Sodium hypochlorite	--	66,000	66,000	--
Ferric chloride	--	2,700	--	--
Fleet and equipment use (miles/yr)[2]				
Heavy-duty truck				6,200
Light-duty truck				140,000
Hybrid vehicle				4,300
Automobile				2,400

Notes: NA = Not available. DI = Ductile iron. AC = Asbestos cement. PE = Polyethylene.

[1] Year 2009 data for electricity and chemical use. Treatment electricity was estimated based on the average increased electricity use above supply for wells with treatment given the well's depth and average flow. Electricity use for disinfection is assumed to be marginal compared to pumping of the well. An additional 114 kWh of electricity use for administrative purposes is included in the final results.

[2] Fleet data based on nine-months of use in 2009-2010; fleet use was distributed between the supply (25%), treatment (25%), and distribution (50%) systems for this analysis.

9.2 Task 9 Outcomes

9.2.1 Revisions

The revisions to WEST and WWEST have improved the tools in a number of ways, most notably by providing more recent and/or more applicable EFs for energy production, including electricity and fuel.

9.2.2 Case Studies

The two case studies described above were analyzed using WEST to evaluate the energy and environmental effects of their infrastructure and operations. Results are reported in terms of environmental effect per million liters (Mℓ).

9.2.2.1 Large Utility

NC-Large uses three water sources, all of which were analyzed as separate water sources and as a combination to represent typical water in the "system". The results of the NC-Large analysis for the sources and system are summarized in Table 47.

Table 47: NC-Large Results Summary for Sources and System

Constituent per Mℓ	Source: Imported	Source: Reservoir	Source: Stored	Overall System
Energy (GJ)	4.2	15	16	5.6
GHGs (kg)	260	870	910	330
NO_x (g)	720	2200	2300	890
PM (g)	280	700	790	330
SO_x (g)	530	2100	2100	720
VOC (g)	2700	4300	4400	2900
CO (g)	1300	2100	2400	1400

In contrast to results from prior case studies, imported water is preferable to other water sources, including local water. The water is imported through gravity aqueducts and little, if any, energy is used to transport it. Water stored in reservoirs requires more pumping than imported water. In addition, reservoir and stored water require more significant treatment, including increased energy and chemical consumption, than the more pristine imported water.

Figure 20 shows the breakdown of the system energy consumption results by life-cycle phase (construction, operation, maintenance) and demonstrates that system operation contributes two-thirds of the results. Operation consists primarily of energy and chemical consumption on a day-to-day basis. Construction uses one quarter of the energy. End of life, which consists solely of sludge disposal, is negligible (less than 0.1 percent).

Figure 20: NC-Large System Energy Results by Life-cycle Phase

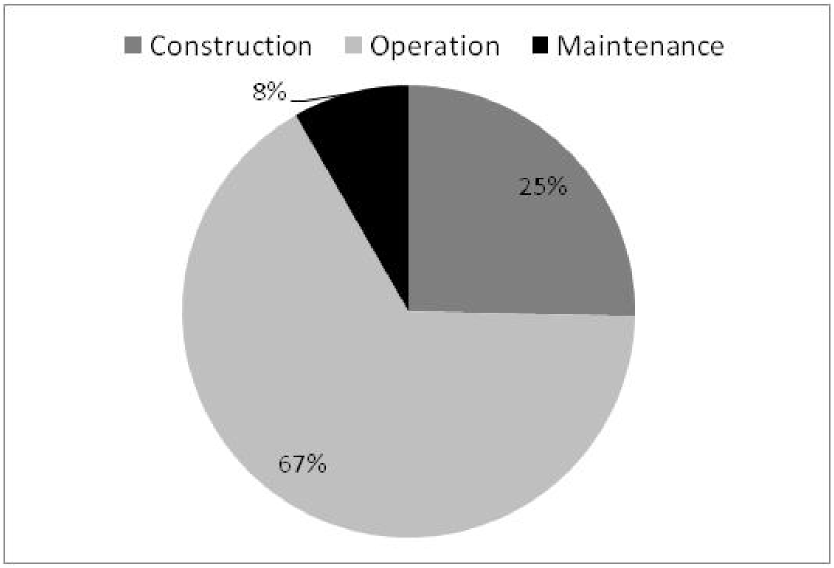
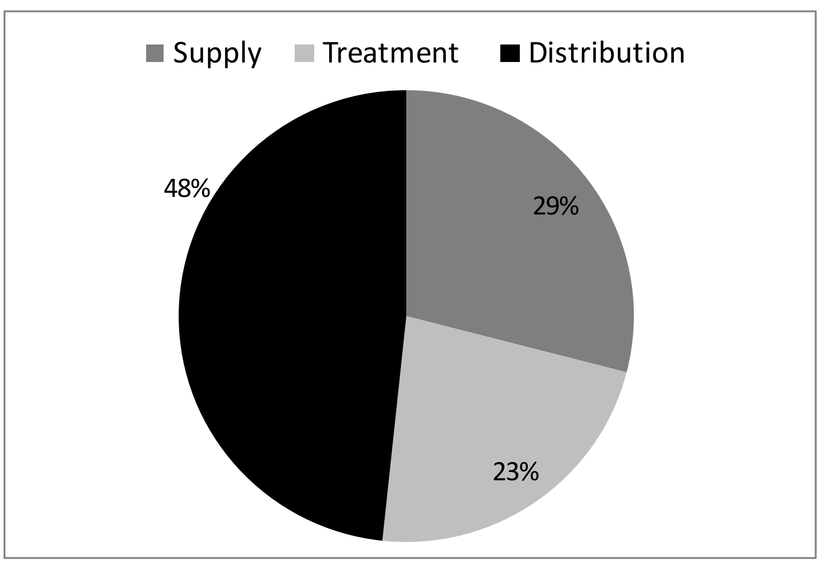


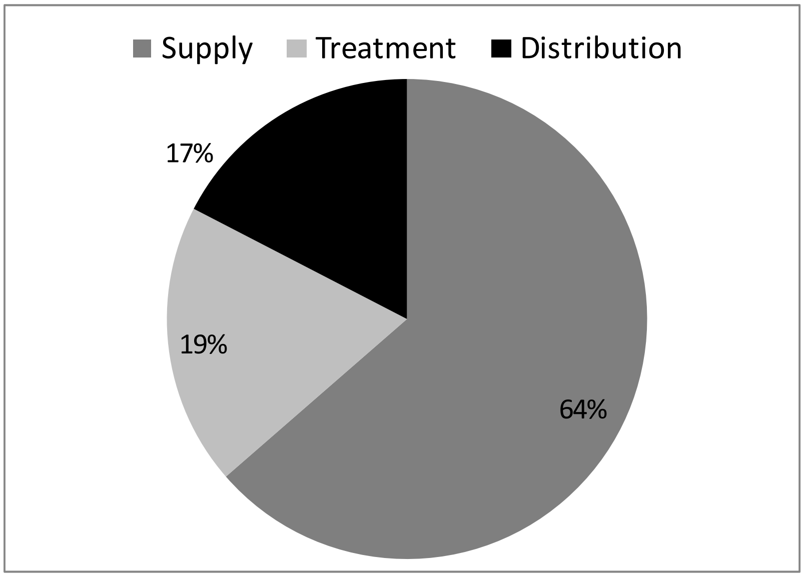
Figure 21 summarizes the system energy results by water supply phase. The supply phase (29 percent) consists of aqueducts, reservoirs, and pump stations. The treatment phase (23 percent) includes all activities at the treatment plants, including filter replacement and chemical consumption. The distribution phase (48 percent) is composed of pipes, pumps stations, tanks, and valves needed to move treated water to customers in the service area.

Figure 21: NC-Large System Energy Results by Water Supply Phase



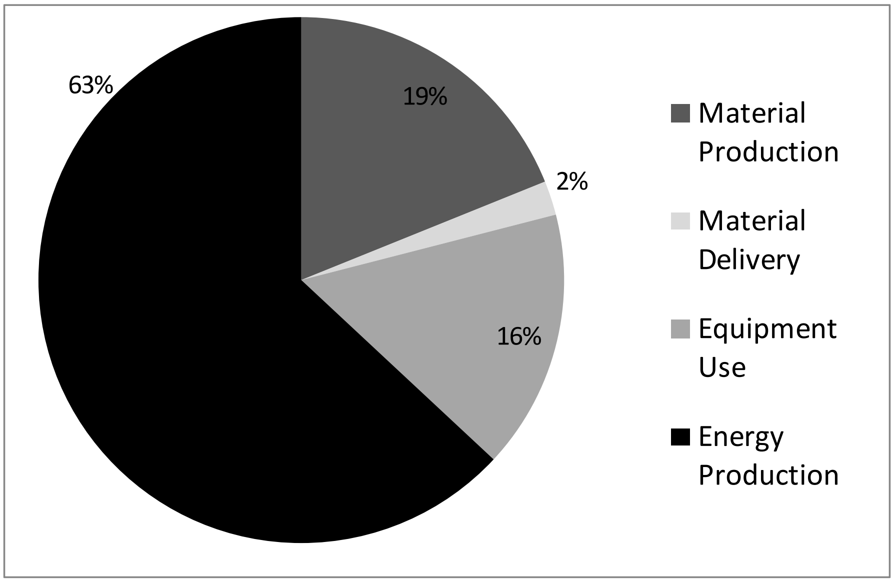
The system results consist primarily of imported water. Figure 22 shows the same breakdown for the local reservoir component of the water supply. In this case, the supply phase comprises about two-thirds of the results.

Figure 22: NC-Large Reservoir Energy Results by Water Supply Phase



Five activities are included in WEST: material production, material delivery, equipment use, energy production, and sludge disposal. Figure 23 shows energy results by activity. The sludge disposal activity is not shown because it contributed negligibly (<0.1 percent). The most significant activity is energy production, primarily electricity use and natural gas consumption. Material production and equipment use are also important at 19 percent and 16 percent, respectively. The equipment use results are more significant than seen in prior case studies because the utility provided information on fleet vehicle use, excluded from prior studies due to lack of data.

Figure 23: NC-Large System Energy Results by Activity



9.2.2.2 Small Utility

NC-Small obtains all of its water from local groundwater. About half of the water must be treated to remove sediment and minerals; the remainder is more pristine and is only disinfected. The two levels of water treatment, full treatment and disinfection only, are reported separately along with the overall system results in Table 48.

Table 48: NC-Small Results Summary for Sources and System

	Source		
Constituent per million liters	**Treated Groundwater**	**Disinfected Groundwater**	**Overall System**
Energy (GJ)	20	19	20
GHGs (kg)	1400	1300	1400
NO_x (g)	3600	3400	3500
PM (g)	880	840	860
SO_x (g)	2000	2000	2000
VOC (g)	1700	1700	1700
CO (g)	2100	1900	2000

The additional treatment needed for the less pristine water (i.e., filtration, chemical addition) does not add appreciably to the final results because most of the environmental effects are caused by pumping in the supply and distribution system.

Figure 24 shows the breakdown of the NC-Small energy consumption results by life-cycle phase and demonstrates that operation contributes over 90 percent of the results. Operation consists primarily of energy and chemical consumption on a day-to-day basis. Construction uses eight percent of the energy. Maintenance contributes less than 1 percent. The geographically smaller scale system requires less infrastructure, and therefore less construction and maintenance, than NC-Large.

Figure 24: NC-Small System Energy Results by Life-cycle Phase

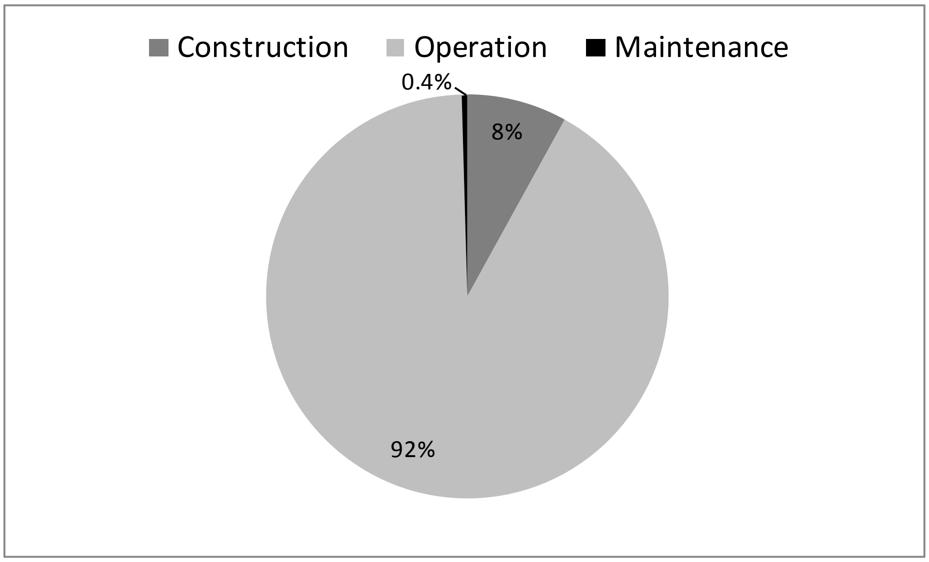


Figure 25 summarizes the NC-Small energy results by water supply phase. The supply phase (33 percent) consists of groundwater wells. The treatment phase (20 percent) includes activities at the treatment plants, including chemical consumption. The distribution phase (47 percent) is composed of pipes, pumps stations, tanks, and valves needed to move treated water to customers. The treatment process is less complex for NC-Small and, therefore, the treatment contribution is lower. However, though the groundwater is local, the supply contribution is larger than NC-Large's predominately imported water supply. The pumping required to extract it from the aquifers is more significant than NC-Large's gravity-fed aqueduct.

Figure 25: NC-Small System Energy Results by Water Supply Phase

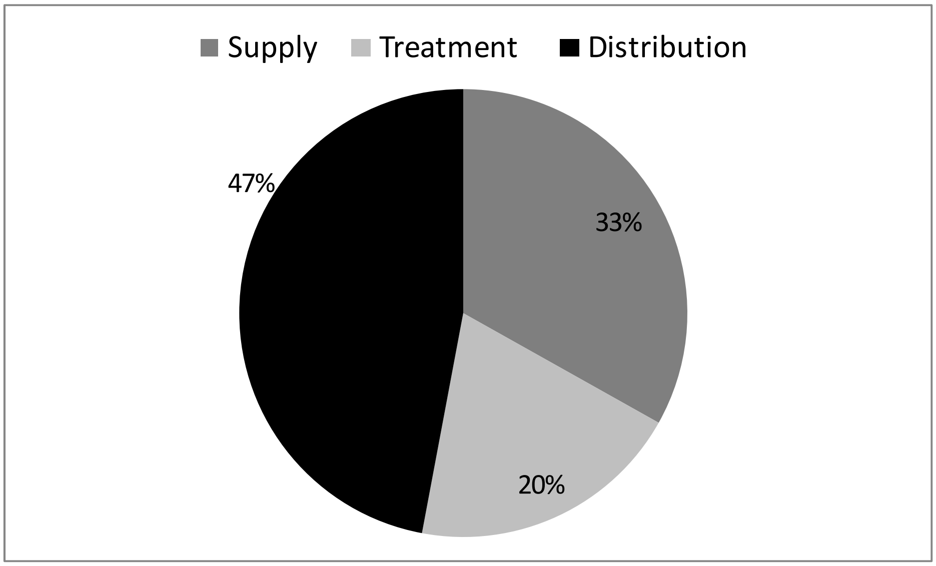
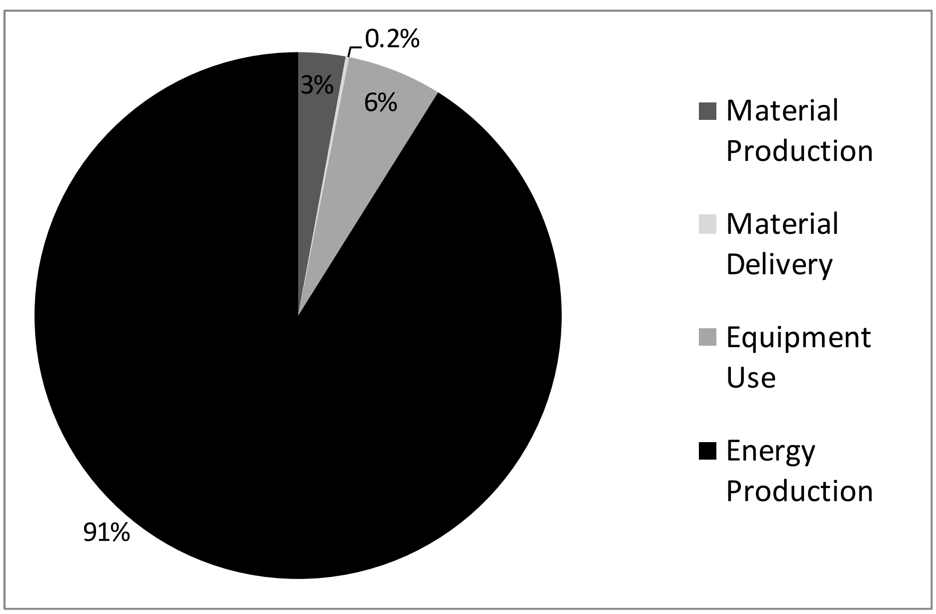


Figure 26 shows NC-Small's energy results broken out by activity. The most significant activity is energy production (92 percent). The small scale system and simple treatment process results in low material production results relative to prior case studies (2 percent).

Figure 26: NC-Small System Energy Results by Activity



9.3 Task 9 Conclusions and Recommendations

The revisions completed as part of Task 9 will provide tool users a more updated and user-friendly analysis of their water and wastewater utilities.

The results of the case study analysis of a Northern California utility differ significantly from prior analyses and highlight the range of results that can be expected for water systems in the state, depending on water sources, system design, geography, and other factors. In contrast to other analyses, imported water appears to be preferable to the local reservoir water collected in the service area. The geography of the imported source allows the water to be gravity-fed to the utility so electricity use is minimized. Furthermore, the treatment required for stored water is more significant than for water directly imported, increasing the advantage.

CHAPTER 10:
Task 10 – Analyze the Energy Demand of Wastewater Systems

Collection, treatment, and disposal of wastewater are significant sources of energy consumption and associated environmental emissions (CEC 2005). LCAs of wastewater systems have been conducted in other countries (see Chapter 1) and indicate that the treatment process is a significant contributor to overall electricity consumption, that the sludge treatment process can be a significant source of GHG emissions, that sludge disposal also contributes to total environmental emissions though in some cases it can reduce GHG emissions, and that treatment process choices can affect electricity use as well as GHG emissions.

The researchers created an MS Excel-based decision-support tool to assess California wastewater systems. The structure and framework of the tool is similar to WEST. The Wastewater Energy Sustainability Tool (WWEST) and an analysis of a wastewater utility are further described in the following sections. This work was also published in Stokes and Horvath (2010).

10.1 Task 10 Approach

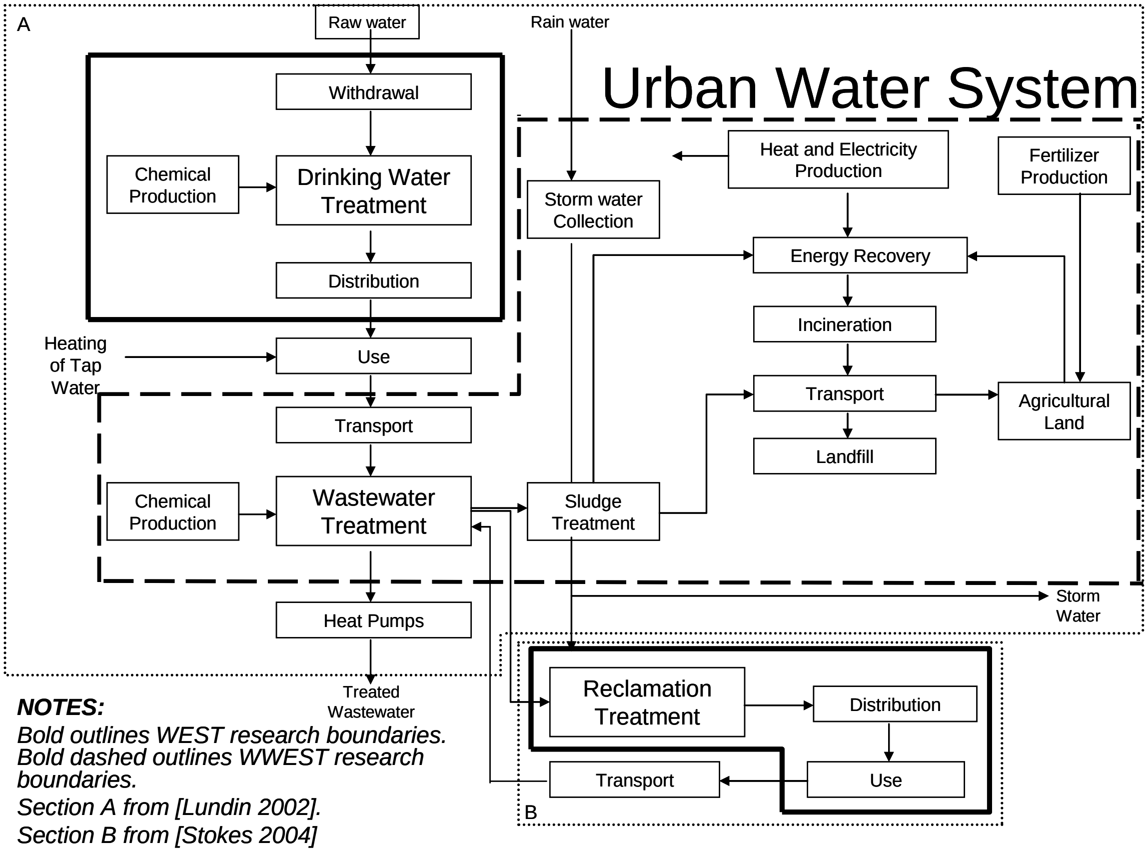
The framework of this study was to conduct an LCA of a large wastewater utility. LCA has been previously described in Chapter 1. Similarly to WEST, WWEST incorporates a form of hybrid LCA which leverages the strengths of each approach while minimizing the disadvantages. EIO-LCA was used to estimate emissions due to manufacturing most of the materials used in the system. EIO-LCA is not detailed enough to assess the operation phase. Operational effects (e.g., fleet vehicle emissions, electricity generation) were estimated using process-based LCA. Process-based LCA data were also used to obtain more accurate results for certain manufactured materials, including plastic pipe and treatment chemicals (see Chapter 9).

10.1.1 The Wastewater-Energy Sustainability Tool

WWEST employs user-defined input data to evaluate emissions and energy use throughout the system life-cycle, including construction, operation, maintenance, and end of life. The end-of-life phase includes only the environmental effects of sludge disposal. Decommissioning of the system, another consideration in most end-of-life analyses, is not included because sufficient data were not available. Additionally, a water system LCA found that decommissioning contributed less than 1 percent of the overall environmental burden (Friedrich 2002). The contribution for a wastewater system is expected to be similar.

The tool evaluates energy and material use for six categories of activities: material production, material delivery, equipment use, energy production, sludge disposal, and direct emissions from the treatment processes. Figure 27 shows the boundaries which define the analysis in this study as well as the components included in the Phase One work.

Figure 27: Research Boundaries



Material production assessment allows the user to inventory materials used in the system and evaluate the energy and environmental effects of their manufacture or provision throughout the supply chain using EIO-LCA and GaBi. Materials include reinforced concrete, pipe, pumps, valves, electrical and control systems, and chemical storage equipment. Table 49 describes more fully the components of the wastewater system and supply chain included in the study.

The material delivery component assesses the emissions produced from and energy used to transport materials to the end-use location by truck, train, ship, or airplane. Airplane transport might be appropriate for emergency delivery. Alternately, the airplane EFs could be used to analyze the effects of employee travel.

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; fuel production was assessed using EIO-LCA.

Table 49: LCA System Boundaries

Life-cycle Phase	Summary of Activities in Boundary
Construction	-Fuel use & emissions for construction equipment & delivery vehicles;
	-Energy use & emissions for production of construction materials, treatment equipment, & energy used in initial installation, including the supply chain.
Operation	-Energy & emissions for operating collection, treatment, & discharge phases;
	-Energy generation offsets from treatment operation;
	-Fuel use & emissions for delivery & operational vehicles;
	-Energy use & emissions from producing chemicals & other routinely used materials (including supply chain);
	-Direct emissions from the treatment process.
Maintenance	-Energy use & emissions used to produce replacement parts for materials with service lives shorter than the analysis period (including supply chain);
	-Fuel use & emissions from maintenance & delivery vehicles.
End-of-life	-Fuel use & emissions for transporting & disposing of sludge;
	-Long term emissions, energy generation offsets, & fertilizer production offsets from disposal site (e.g., landfill).

Each item entered in the tool must be categorized by the user according to life-cycle phase, construction, operation, maintenance or end of life, defined as follows:

- *Construction* includes facility construction and production, delivery, and installation of equipment present at system start-up, as well as construction equipment operation.
- *Operation* includes 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.
- *End of life* includes all activities associated with sludge disposal once it has been treated fully, mainly transport, final disposal, and electricity and/or fertilizer offsets.

In addition, each item should be defined as a component of the wastewater process: collection (transporting water through sewer lines to the treatment plant), treatment (ensuring discharged water meets regulatory standards), or discharge (transporting treated water to the discharge point). WWEST could be useful for several audiences, including planners, designers, construction contractors, plant operators, utility administrators, and policy analysts. WWEST can evaluate the environmental effects when:

- comparing distributed treatment to centralized systems when designing for expansion
- changing treatment process to reduce emissions to receiving waters or adjusting to changes in air emission standards;

- evaluating alternative treatment for filtration, disinfection, or natural treatment processes; and
- choosing materials for infrastructure improvements, such piping material (e.g., steel , concrete, plastic, iron).

Generally, 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.

WWEST is an Excel-based spreadsheet and contains worksheets in five categories: (1) data entry, (2) data, (3) calculations, (4) results, and (5) help. These worksheet types are discussed in the following sections. Appendix A.2 contains a copy of WEST. The WWEST user manual and revision log are in Appendix A.2.1 and A.2.2., respectively. Additional documentation specific to this task is included in the explanatory (HELP) pages in Appendix A.2.3. Appendix A.2.3 covers general tool information, including formatting conventions, acronyms and abbreviations, and general equations. Appendix A.2.3 also includes documentation of all data entry cells, provides documentation of the assumptions and calculations used in WWEST, and summarizes the references by topic area.

10.1.1.1 Data Entry Worksheets

The data entry pages allow the user to input system information. Two types of worksheets are included in this category: entry and assumption worksheets. The entry sheets allow the user to provide information needed to perform basic calculations. The assumptions pages allow the user to review and revise default assumptions and provide more detailed data. Additional information will improve the overall tool output and provide more accurate results.

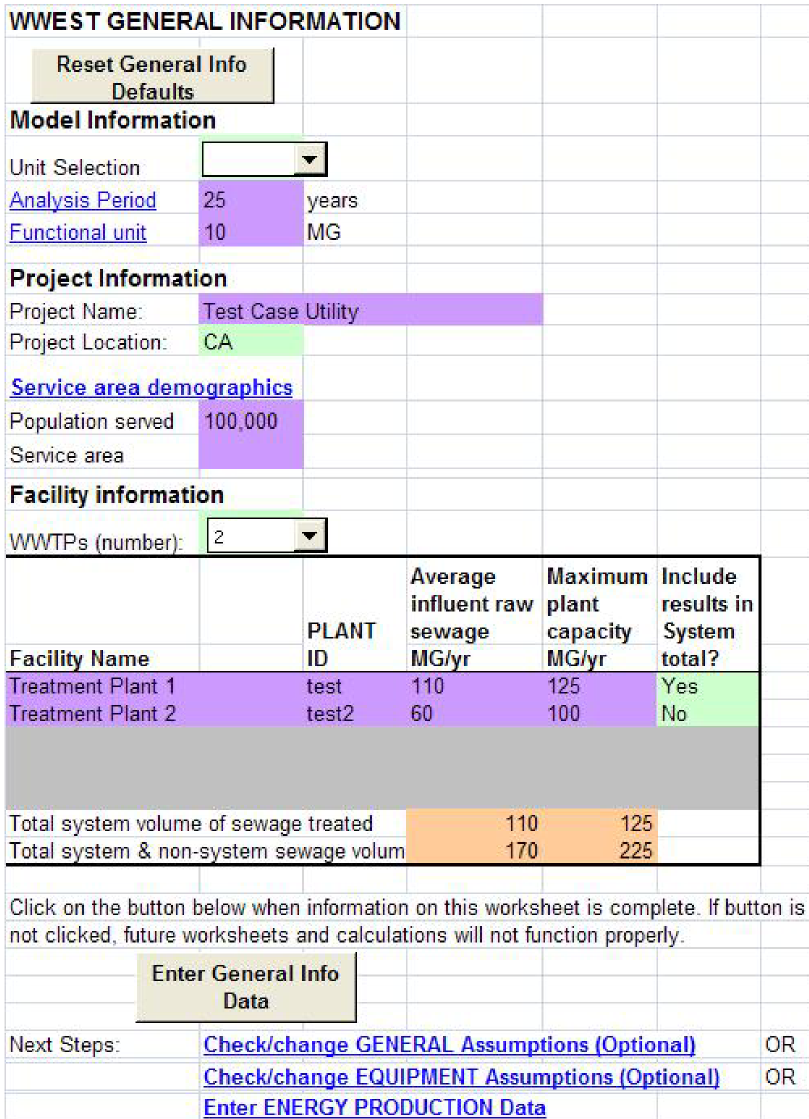
A general information page (Entry-General worksheet) requires the user to define model assumptions (units, analysis period, and functional unit), the name, location, and demographics of the system, and WWTP characteristics. Up to five WWTPs can be defined. Figure 28 shows the general data entry worksheet.

The following cell color convention is used in WWEST to help clarify data entry process:

- green cells - user selects from a drop-down menu,
- purple cells - user enters data (default data may already be shown),
- yellow cells - user may review and/or revise a calculation performed elsewhere,
- tan cells - values are calculated automatically and should not be edited,
- grey cells - unavailable due to lack of data or a prior user selection.

Most entry sheets have a button that allows the user to reset default data, erasing changes the user has made. At the bottom of the sheet, another button allows the user to "Enter" the data. When present, this button must be clicked before moving on to ensure the tool calculates properly. Hyperlinks at the bottom of the page direct the user to the next worksheets to be completed in the data entry process. Only one of these hyperlinks will link to a page with required data entry; multiple links to optional data entry pages may be present. For complete data entry, visit the all worksheets listed in the hyperlinks from top to bottom.

Figure 28: General Information Data Entry Worksheet



The Assump-GEN allows the user to see the time horizon for global warming calculations, define the default cost reporting year for user-entered costs (costs provided in WWEST in 1997$, unless noted). If desired, the user can edit the service life, delivery modes, and delivery distances for pre-defined materials or define custom materials on this sheet.

On a separate worksheet (Assump-Equip), the user enters construction, transportation, and maintenance equipment data. This page allows the user to define the size, model year, engine capacity, productivity, fuel type, and fuel use of equipment. For instance, the user can select the excavator model used for construction and the type of dump truck used for sludge disposal. The worksheet contains predefined equipment characteristics, but the user can define more precise information if desired. In addition, the user can enter custom equipment parameters.

The user should also enter preferences for energy production analysis (Entry-EP). The user should select whether to use direct EFs (i.e., smokestack emissions only) or lifecycle EFs, which include the supply chain effects of mining, processing, and transporting fuel. In addition, the user can select whether they would like to use United States average EFs, state average emissions factors for the state selected on the Entry-GEN worksheet, or a custom generation mix. Based on the user's selection from the two drop-down menus, default EFs will be added to the electricity and natural gas EFs. The user can edit these EFs as needed.

The remaining Entry pages are defined by the wastewater phase (collection, treatment, or discharge). This division is intended to be more intuitive for the user's data entry process than division by activity as done in WEST and to simplify data entry for the user. The collection and discharge system entry pages (Entry-COL and Entry-DIS, respectively) are similar and therefore discussed together. Information about pipe length, valves, flowmeters, manholes and curb inlets (for the collection system only), lift stations and pumps, and energy consumption can be entered in the tables. There are also tables where other materials and equipment use can be entered. The assumption pages for collection and discharge (Assump-COL and Assump-DIS, respectively) allow the user to define an average pipe depth and interval for fittings. The user can also enter additional information about lift stations and other buildings.

There are several data entry pages for treatment data due to the complexity of wastewater treatment. The main treatment entry page (Entry-TRT) allows the user to define unit processes used at each WWTP, piping requirements, pump sizes and numbers, energy used (electricity, natural gas, gasoline, and diesel), energy recovered (electricity and heat), chemical use, storage, and delivery data for liquid and sludge treatment, sludge production, and CH_4 capture rates. Additional material use and equipment operation can be entered in tables at the bottom.

Liquid treatment processes which can currently be assessed by WWEST include: screening (course and fine/micro), grinding, grit removal, flow equalization and storage, rapid mixing, coagulation and flocculation, sedimentation and clarification, filtration (conventional and membrane), activated sludge, ponds and lagoons, carbon adsorption, and disinfection by chlorinated chemicals and ozone.

WWEST could be improved by adding the following: primary systems (e.g., septic tanks; added in Task 11); natural systems (e.g., constructed wetlands, rapid infiltration), trickling filters and other aerobic biofilm reactors, membrane bioreactors (MBRs; added in Task 11), ultraviolet (UV) disinfection (added in Task 11) ion exchange, carbon absorption, and air stripping. Some data about these processes are already present in WWEST but the final calculations have not yet been completed.

Sludge treatment processes which can currently be assessed by WWEST include: grinding, flow equalization and storage, thickening and dewatering techniques (including centrifuge, filter or belt press, vacuum filters, rotary drum filters, thermal drying, gravity thickening, flotation, drying beds), aerobic and anaerobic digestion, chemical thickening, conditioning, stabilization, pH treatment, and pathogen removal. Disposal options include land application, landfill, and incineration

WWEST could be improved by including additional thickening and dewatering techniques, flotation, thermal treatment, wet air oxidation, and disposal by industrial reuse. Some data about these processes are already present in WWEST but the final calculations have not yet been completed. Default data are available in WWEST for many of the liquid and sludge treatment processes and were obtained primarily from (Metcalf and Eddy 2003; Tchobanoglous et al. 2003; Von Sperling and Chernicharo 2005).

An assumption page is included for both liquid and sludge treatment. Assump-LTRT and Assump-STRT allow the user to enter detailed information for unit processess. This may include technology choices (i.e., conventional, extended aeration, or sequencing batch reactors for AS), reactor or tank dimensions, and equipment costs. On the LTRT page, the user can also define tank, basin, or reactor wall dimensions and the number of people served at each plant. On both LTRT and STRT pages, the user can edit default calculations for CH_4 and nitrous oxide (N_2O) emissions for particular treatment processes. Custom CH_4 sources can be defined.

10.1.1.2 Calculation Worksheets

Calculation pages combine user-entered information and standard data to determine energy use and air emissions for all categories. Calculation pages should not be edited by the user. The user should contact the tool developers to suggest changes or correct errors. Three types of calculation pages exist: default, conversion, and calculation pages. Default (Def) worksheets calculate default values which are then automatically entered into the tool using macros triggered by selections made from certain drop-down menus or when the "Enter" buttons at the bottom of some entry pages are clicked. Conversion worksheets (Conv) take user-defined data and convert it into the units needed for calculations. In some cases, default and conversion calculations are present on the same worksheet (DefConv). These pages contain interim calculations and do not necessitate further detail.

Entry pages, and therefore calculation pages, are defined by the wastewater phase (Collection, Treatment, or Discharge), with the exception of energy production and direct GHG emissions which have separate worksheets. This division makes data entry more intuitive for the user than division by activity in WEST but makes calculations more complicated. The environmental effects of multiple activities are calculated on each worksheet, including material production, material delivery, equipment use, sludge disposal, and direct GHG emissions. This section discusses the general calculations associated with each activity as well as data sources for EFs and assumptions. The Help-General worksheet, discussed in detail in Appendix A.2.3, contains the general calculations for these activities.

In most cases, the material production effects are estimated using EFs obtained from the EIO-LCA model (CMU 2007). Each material available in the tool's drop-down menu is associated with an economic sector in EIO-LCA. For some chemicals and plastic materials, EFs were obtained from process-based sources (see Chapter 9 for discussion). The process-based data include a more detailed analysis of manufacture for these materials. Because of the way they were collected, the data are more applicable to the European Union than to United States conditions. However, the authors concluded that the specific manufacturing data make these EFs more appropriate than the United States-focused data from EIO-LCA. Table 50 provides a partial list of common components of a wastewater system included in WWEST and their associated data sources, including EIO-LCA sectors. The default service life and primary delivery distance for each material type are also listed.

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 WWEST. Transport vehicle EFs are from (Facanha and Horvath 2007; OECD 1997).

Table 50: WWEST Material Summary

Material Choices	Emission Factor Source	Emission Factor Sector	Delivery Distance (km)	Service Life (yrs)
Acid, sulfuric	Process	Sulphuric acid	193	1
Activated carbon	Process	Activated carbon	322	3
Adjustable frequency drives	EIOLCA	Relay and industrial control manufacturing	1287	15
Aggregate (not filter media)	EIOLCA	Sand, gravel, clay, and refractory mining	193	100
Alum	Process	Aluminum hydroxide	193	1
Ammonia, aqueous	Process	Ammonia	193	1
Anthracite	EIOLCA	Coal mining	4023	12
Asphalt	EIOLCA	Asphalt paving mixture & block manufacturing	129	20
Blowers	EIOLCA	Industrial & commercial fan & blower manufacturing	483	30
Buildings, industrial	EIOLCA	Manufacturing and industrial buildings	322	50
Calcium hypochlorite	Process	Calcium hypochlorite	193	1
Caustic soda	Process	Caustic soda	193	1
Chemicals, industrial	EIOLCA	Other basic inorganic chemical manufacturing	193	1
Chlorine, compressed/liquified	Process	Chlorine	193	1
Concrete, precast	EIOLCA	Other concrete product manufacturing	386	75
Concrete, ready-mixed	EIOLCA	Ready-mix concrete manufacturing	129	100
Controls	EIOLCA	Relay and industrial control manufacturing	386	15
Electrical equipment	EIOLCA	Misc. electrical equipment manufacturing	386	15
Ferric chloride	Process	Ferric chloride	193	1
Generators	EIOLCA	Motor and generator manufacturing	1609	30
Gravel filter media	EIOLCA	Sand, gravel, clay, and refractory mining	322	10
Industrial equipment, electrical	EIOLCA	Misc. electrical equipment manufacturing	515	15
Industrial equipment, general	EIOLCA	General ind machinery and equip n.e.c.	515	15
Ion exchange resin	Process	Ion-exchange resin	3862	5
Membrane, cellulose acetate	Process	Cellulosic organic fiber manufacturing	1931	6
Membrane, PVDF	Process	Polyvinylidenefluoride (PVDF)	1931	6
Meters, flow	EIOLCA	Totalizing fluid meters and counting devices	1287	15
Mortar	EIOLCA	Clay refractory and other structural clay	322	15
Motors	EIOLCA	Motor and generator manufacturing	515	30
Natural Gas	EIOLCA	Natural gas distribution	193	1
Ozone	Process	Ozone	193	1
Pipe, concrete	EIOLCA	Concrete pipe manufacturing	257	75
Pipe, cast and ductile iron	EIOLCA	Iron and steel pipe	257	60
Pipe, PE	EIOLCA	Plastics pipe, fittings, and profile shapes	257	60
Pipe, PVC	EIOLCA	Plastics pipe, fittings, and profile shapes	257	60
Pipe, steel	EIOLCA	Iron and steel pipe	257	75
Pipe, vitrified clay	EIOLCA	Brick and structural clay tile manufacturing	257	75
Polymers	Process	Polymer	290	1
Pumps	EIOLCA	Pump & pumping equipment manufacturing	515	30
Rebar	EIOLCA	Iron and steel mills	193	100
Sand filter media	EIOLCA	Sand, gravel, clay, and refractory mining	322	10
Sodium hypochlorite	EIOLCA	Other basic inorganic chemical manufacturing	193	1
Tanks, steel	EIOLCA	Iron and steel forging	1287	75
Turbines	EIOLCA	Turbine & turbine generator manufacturing	1931	30
Valves and fittings, metal	EIOLCA	Metal valve manufacturing	257	20
Wood	EIOLCA	Sawmills	129	40

Note: Misc. = Miscellaneous

Equipment use emissions are a function of model year, equipment type, motor capacity, and amount of use. Sources for EFs follow: diesel road vehicles (USEPA 1995), diesel non-road vehicles and equipment (CARB 2002), passenger cars and light trucks (Chester and Horvath 2009), other gasoline vehicles and equipment (USEPA 1996), and electric equipment (USEPA 2007) are provided. The EFs are included in Appendix A.2.3. The general equation used to calculate emissions is provided in Appendix A.2. Equipment data are from a variety of sources, e.g., (Caterpillar 1996; Means 1997; John Deere 2004).

Sludge disposal calculations estimate the effects of transport and long-term disposal of treated sludge. Disposal alternatives include landfilling, incineration, land application, and industrial reuse. The EFs are from several sources, including (Dennison 1996; USEPA 2006).

GHGs are emitted directly from certain treatment processes at some WWTPs. Trace amounts of N_2O are emitted through nitrification/denitrification processes. Methane is emitted from anaerobic reactors, lagoons, and digesters. Other aerobic treatment processes, if not properly managed, can become anaerobic and emit CH_4 as well. Both N_2O and CH_4 are emitted when sludge is disposed by landfilling, composting, and incineration. Emission factors for these processes are from (IPCC 2006). The EFs can be edited by the user depending on specific system operation.

Energy production emissions are calculated on the Calcs-EP worksheet and include emissions due to refining fuel for use in delivery vehicles and construction equipment, as well as emissions caused from electricity generation. Fuel production emissions are evaluated using EFs from the GREET model (see Chapter 9 for details). National and statewide electricity generation EFs were obtained from EPA's EGRID model (USEPA 2007). These EFs are specific to the energy mix for the U.S. or for any state. Direct emissions for specific electricity sources (coal, natural gas, oil, and biomass) are also obtained from EGRID. These emissions are combined with estimates of indirect emissions from the literature (see Chapter 5). Natural gas combustion EFs are from (USEPA 1998). Default EFs for combusting CH_4 for electricity production are also present. The EFs are taken from the direct natural gas EFs from EGRID, except that the GHG EF is assumed to be zero because the CH_4 is biogenic and is considered inevitable. Lifecycle effects are not included as fuel mining/transport will not be needed.

10.1.1.3 Results Worksheets

Results from the cumulative calculations are displayed both numerically and graphically on the results pages. Results display information according to life-cycle phase wastewater phase, and activity category (material production, material delivery, equipment use, energy production, direct emissions, and sludge disposal). Energy use, GHG, and air emissions (NOx, PM, SOx, VOC, and CO) are reported in terms of average annual emissions per functional unit of treated wastewater. Figure 29 presents a sample results page for data to show how tabular results are presented. Figure 30 presents a sample graphs results page. On the Graphs worksheet , the user can customize the graphs to provide more appropriate and meaningful results. The results shown are for demonstration only and are not intended to be representative for any wastewater system.

Figure 29: WWEST Sample Results Data Worksheet

TABLE 1: Summary Results

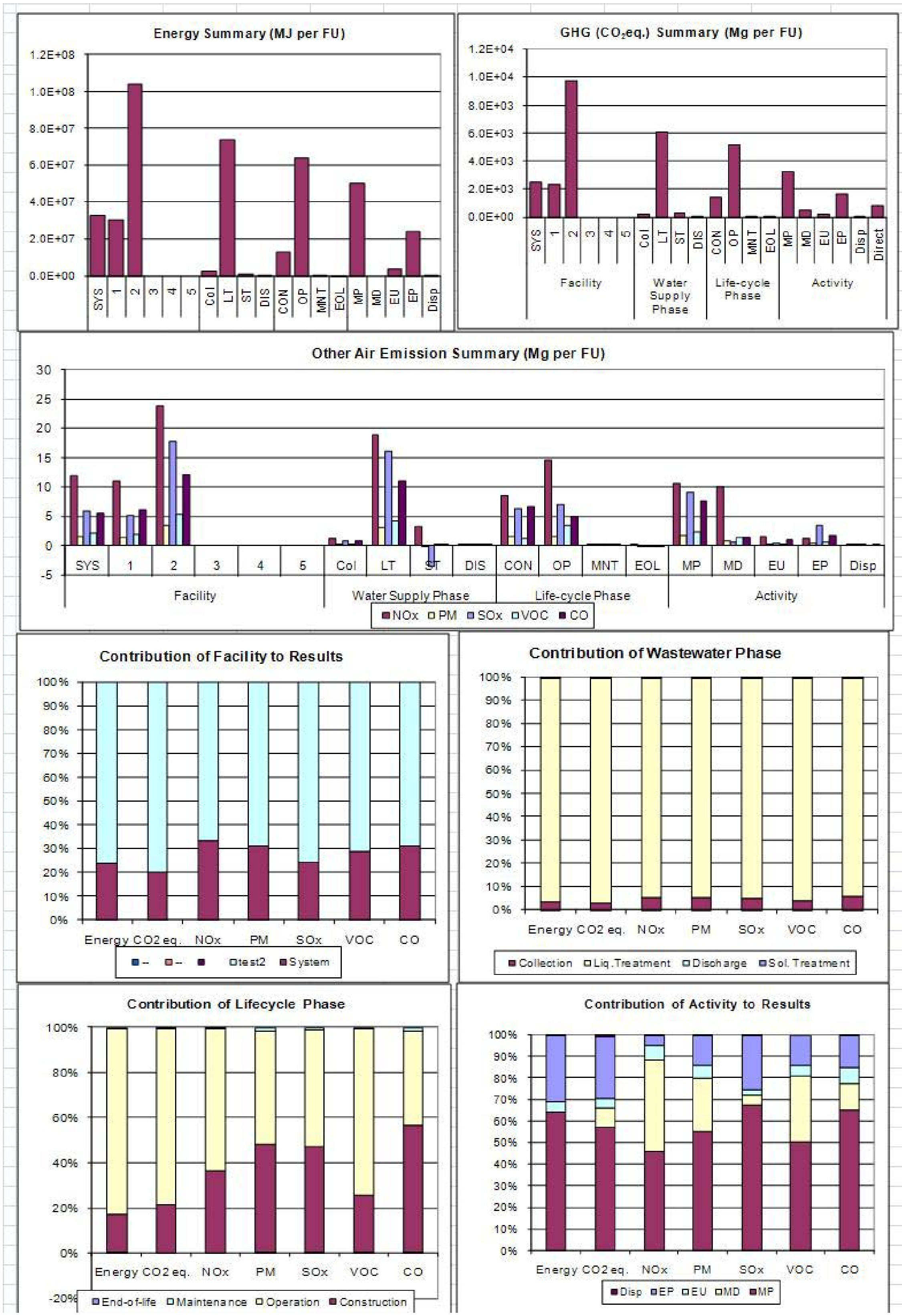
Chem-		Weighted	Facility						Water Supply Phase				Life-cycle Phase				Activity					
ical	Total	Total	SYS	1	2	3	4	5	Col	LT	ST	DIS	CON	OP	MNT	EOL	MP	MD	EU	EP	Disp	Direct
Results per functional unit (MJ for energy, Mg for other)									Functional unit =			1.0E+01	MGD									
Energy	2E+08	8E+07	3E+07	3E+07	1E+08	0E+00	0E+00	0E+00	3E+06	7E+07	8E+05	1E+05	1E+07	6E+07	4E+05	-2E+05	5E+07	7E+00	4E+06	2E+07	4E+04	
CO_2 eq.	1E+04	7E+03	3E+03	2E+03	1E+04	0E+00	0E+00	0E+00	2E+02	6E+03	3E+02	9E+00	1E+03	5E+03	3E+01	1E+01	3E+03	5E+02	2E+02	2E+03	3E+01	9E+02
NO_x	5E+01	2E+01	1E+01	1E+01	2E+01	0E+00	0E+00	0E+00	1E+00	2E+01	3E+00	4E-02	8E+00	1E+01	1E-01	1E-02	1E+01	1E+01	2E+00	1E+00	3E-02	
PM	6E+00	3E+00	2E+00	1E+00	3E+00	0E+00	0E+00	0E+00	2E-01	3E+00	-1E-01	8E-03	2E+00	2E+00	5E-02	-1E-02	2E+00	8E-01	2E-01	4E-01	8E-03	
SO_x	3E+01	1E+01	6E+00	5E+00	2E+01	0E+00	0E+00	0E+00	9E-01	2E+01	-3E+00	4E-02	6E+00	7E+00	1E-01	-7E-03	9E+00	6E-01	4E-01	3E+00	5E-03	
VOC	9E+00	5E+00	2E+00	2E+00	5E+00	0E+00	0E+00	0E+00	2E-01	4E+00	1E-01	9E-03	1E+00	3E+00	4E-02	-6E-03	2E+00	1E+00	2E-01	7E-01	0E+00	
CO	2E+01	1E+01	6E+00	6E+00	1E+01	0E+00	0E+00	0E+00	7E-01	1E+01	7E-02	4E-02	7E+00	5E+00	2E-01	-8E-04	8E+00	1E+00	9E-01	2E+00	3E-02	
Results (% of total)																						
Energy	--		20%	18%	62%	0%	0%	0%	4%	95%	1%	0%	17%	83%	1%	0%	64%	0%	5%	31%	0%	
CO_2 eq.	--		17%	16%	67%	0%	0%	0%	3%	92%	4%	0%	21%	78%	0%	0%	50%	8%	4%	25%	1%	1E-01
NO_x	--		26%	24%	51%	0%	0%	0%	5%	81%	14%	0%	37%	63%	1%	0%	46%	43%	7%	5%	0%	
PM	--		24%	22%	53%	0%	0%	0%	6%	98%	-4%	0%	49%	50%	2%	0%	55%	25%	6%	14%	0%	
SO_x	--		20%	18%	62%	0%	0%	0%	6%	119%	-26%	0%	47%	52%	1%	0%	67%	4%	3%	25%	0%	
VOC	--		23%	21%	56%	0%	0%	0%	4%	93%	3%	0%	26%	74%	1%	0%	50%	31%	5%	14%	0%	
CO	--		23%	25%	51%	0%	0%	0%	6%	93%	1%	0%	56%	42%	2%	0%	65%	12%	8%	15%	0%	

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

TABLE 2: Detailed Results

				Results per functional unit (MJ for energy, Mg for other)							Results (% of total)						
		Chemical		Energy	CO_2 eq.	NO_x	PM	SO_x	VOC	CO	Energy	CO_2 eq.	NO_x	PM	SO_x	VOC	CO
System	Col	CON	MP	1.3E+06	8.7E+01	5.3E-01	1.0E-01	4.9E-01	7.6E-02	4.2E-01	1%	1%	1%	2%	2%	1%	2%
			MD	1.5E-01	1.1E+01	2.0E-01	1.6E-02	1.2E-02	2.8E-02	2.9E-02	0%	0%	0%	0%	0%	0%	0%
			EU	1.0E+05	6.8E+00	4.7E-02	6.9E-03	1.3E-02	5.8E-03	2.5E-02	0%	0%	0%	0%	0%	0%	0%
			EP	1.8E+04	1.0E+00	5.7E-03	9.7E-04	5.2E-03	2.2E-03	4.3E-03	0%	0%	0%	0%	0%	0%	0%
		OP	MP	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
			MD	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
			EU	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
			EP	7.4E+05	5.3E+01	3.1E-02	9.0E-03	1.2E-01	2.2E-02	3.4E-02	0%	0%	0%	0%	0%	0%	0%
		MMT	MP	8.4E+04	5.6E+00	2.1E-02	4.3E-03	2.7E-02	6.4E-03	3.6E-02	0%	0%	0%	0%	0%	0%	0%
			MD	1.6E-02	1.2E+00	2.3E-02	1.8E-03	1.3E-03	3.2E-03	3.2E-03	0%	0%	0%	0%	0%	0%	0%
			EU	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
			EP	2.8E-03	1.6E-07	8.7E-10	1.5E-10	7.9E-10	3.3E-10	6.6E-10	0%	0%	0%	0%	0%	0%	0%
	DIS	CON	MP	7.0E+04	4.8E+00	2.7E-02	5.1E-03	2.6E-02	4.8E-03	2.3E-02	0%	0%	0%	0%	0%	0%	0%
			MD	3.7E-04	2.7E-02	5.1E-04	4.0E-05	3.0E-05	7.2E-05	7.3E-05	0%	0%	0%	0%	0%	0%	0%
			EU	1.1E+02	8.0E-03	4.2E-05	6.0E-06	1.6E-05	3.0E-06	1.5E-05	0%	0%	0%	0%	0%	0%	0%
			EP	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
		MMT	MP	2.5E+04	1.7E+00	6.6E-03	1.2E-03	8.2E-03	2.1E-03	1.0E-02	0%	0%	0%	0%	0%	0%	0%
			MD	3.7E-04	2.7E-02	5.1E-04	4.0E-05	3.0E-05	7.2E-05	7.3E-05	0%	0%	0%	0%	0%	0%	0%
			EP	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
test	LT	CON	MP	4.1E+06	5.3E+02	2.9E+00	5.8E-01	2.7E+00	3.9E-01	2.6E+00	2%	4%	6%	9%	9%	4%	11%
			MD	1.5E-01	1.1E+01	2.0E-01	1.6E-02	1.2E-02	2.8E-02	2.9E-02	0%	0%	0%	0%	0%	0%	0%
			EU	1.5E+06	9.6E+01	7.1E-01	6.9E-02	1.8E-01	9.4E-02	3.9E-01	1%	1%	2%	1%	1%	1%	2%
			EP	8.8E+02	6.3E-02	3.7E-05	1.1E-05	1.4E-04	2.6E-05	4.1E-05	0%	0%	0%	0%	0%	0%	0%
		OP	MP	4.3E+06	2.5E+02	8.8E-01	1.7E-01	8.7E-01	3.3E-01	7.5E-01	3%	2%	2%	3%	3%	3%	3%
			MD	2.7E+00	2.0E+02	3.8E+00	2.9E-01	2.2E-01	5.3E-01	5.4E-01	0%	1%	8%	5%	1%	6%	2%
			EU	3.0E+05	2.0E+01	3.1E-02	2.2E-02	0.0E+00	1.4E-02	3.2E-02	0%	0%	0%	0%	0%	0%	0%
			EP	2.8E+07	2.0E+03	1.2E+00	4.1E-01	4.3E+00	7.9E-01	1.2E+00	17%	13%	3%	7%	15%	8%	5%
			Direct		6.4E+01												
		MMT	MP	1.0E+05	6.8E+00	2.7E-02	5.2E-03	2.9E-02	8.0E-03	4.8E-02	0%	0%	0%	0%	0%	0%	0%
			MD	9.5E-04	7.0E-02	1.3E-03	1.0E-04	7.7E-05	1.8E-04	1.9E-04	0%	0%	0%	0%	0%	0%	0%
			EU	3.1E+03	2.2E-01	1.2E-03	1.7E-04	4.5E-04	8.4E-05	4.2E-04	0%	0%	0%	0%	0%	0%	0%
			EP	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
	ST	CON	MP	1.7E+05	9.6E+00	2.8E-02	1.8E-02	3.2E-02	6.8E-03	3.9E-02	0%	0%	0%	0%	0%	0%	0%
			MD	6.0E-03	4.4E-01	8.3E-03	6.5E-04	4.9E-04	1.2E-03	1.2E-03	0%	0%	0%	0%	0%	0%	0%
			EU	5.1E+04	2.7E+00	2.5E-02	1.7E-03	4.5E-03	4.9E-03	2.1E-02	0%	0%	0%	0%	0%	0%	0%
			EP	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
		OP	MP	1.6E+07	8.2E+02	1.3E+00	1.6E-02	7.0E-01	3.8E-01	1.8E-01	10%	6%	3%	0%	2%	4%	1%
			MD	7.2E-01	5.3E+01	9.9E-01	7.7E-02	5.9E-02	1.4E-01	1.4E-01	0%	0%	2%	1%	0%	1%	1%
			EU	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
			EP	-2.4E+07	-1.7E+03	######	######	#######	-7.0E-01	0.0E+00	-14%	-12%	-2%	-5%	-13%	-7%	0%
			Direct		2.0E+01												
		MMT	MP	2.7E+04	1.8E+00	6.8E-03	1.4E-02	7.7E-03	2.0E-03	1.4E-02	0%	0%	0%	0%	0%	0%	0%
			MD	7.7E-05	5.7E-03	1.1E-04	8.3E-06	6.3E-06	1.5E-05	1.5E-05	0%	0%	0%	0%	0%	0%	0%
			EU	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
			EP	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0%	0%	0%	0%	0%	0%	0%
		EOL	MP	-1.0E+05	-5.8E+00	-8.1E-03	######	-4.8E-03	-4.4E-03	-2.3E-02	0%	0%	0%	0%	0%	0%	0%
			MD	6.2E-03	1.5E-01	3.9E-03	0.0E+00	0.0E+00	1.2E-03	5.5E-03	0%	0%	0%	0%	0%	0%	0%
			EU								0%	0%	0%	0%	0%	0%	0%
			EP	-6.6E+04	-4.7E+00	-2.8E-03	######	-3.1E-03	-1.9E-03	-8.0E-04	0%	0%	0%	0%	0%	0%	0%
			Disp	2.5E+04	9.4E+00	2.1E-02	4.6E-03	2.9E-03	0.0E+00	2.0E-02	0%	0%	0%	0%	0%	0%	0%

Figure 30: WWEST Sample Results Graphs Worksheet



10.1.1.4 Help Worksheets

Help worksheets provide instruction and documentation of WWEST for the benefit of the user. There are five Help worksheets:

- General Help and Instructions (Help-GEN) includes formatting conventions; abbreviations and acronyms; definitions of worksheet types, life-cycle phases, wastewater phases, and activities; general equations used for each activity; the recommended order of data entry; and contact information for tool developers.
- Help - Entry (Help-ENTRY) describes the information which the user should provide in the data entry process.
- Help - Calculations (Help-CALCS) provides the equations and assumptions used in the calculations.
- Help - Results (Help-RESULTS) describes the results presented and provides guidance for the user to utilize these results
- Help - References (Help-REFS) lists the references sorted by topic area.

All Help worksheets are included in their entirety in Appendix A.2.3. Hyperlinks are present throughout WWEST to help the user locate relevant help information while using the tool.

10.1.1.5 Data Worksheets

Data worksheets include all background data used in calculations and can be found in Appendix A.2.3. The following worksheets are included in the data section of the tool:

- Costs and Assumptions (Cost Assump) contains default cost data for piping, valves, tanks, raw materials (e.g., steel and concrete), chemicals and more. It also contains assumptions regarding construction processes (e.g., excess material off-haul distance, soil fluff factor, foundation over-excavation depth) and material unit weights.
- Material production EFs (Matl EFs) provides data collected from EIO-LCA and Gabi.
- Material delivery EFs (MD EFs) lists EFs and sources for the delivery alternatives (local truck, long-distance truck, ship, rail, and plane.
- Equipment Use Data (EU Data) contains equipment productivities and capacities. For example, the number of cubic yards per hour moved by an excavator and the cubic yards carried per dump truck trip are included on this worksheet.
- Equipment use EFs (EU EFs) contains emissions for on- and off-road equipment fueled by gasoline and diesel and for electric-powered equipment. It also contains emissions for natural gas combustion.
- Electricity production EFs (Elect EFs) includes direct and life-cycle EFs for the nation, for all 50 states, and for ten different unique fuels used for electricity production.
- Disposal Factors (Disposal) contains EFs for common disposal alternatives, including landfills, incinerators, and land application.

These are locked and should not be edited by the user. If the user wishes to suggest changes or correct errors, please contact the tool developers. Data references are included on each sheet.

10.1.2 Wastewater Case Study

To simplify future case study analyses, many assumptions are embedded in WWEST. In many cases these assumptions can be edited by the user if they are not appropriate. Default assumptions are summarized in Appendix H.1.

A California wastewater system was analyzed to demonstrate the capabilities of WWEST. The case study system is a large wastewater service utility in California (the utility; the utility asked not to be specifically identified). It serves a population of more than half a million people over an 80 square mile service area which includes multiple communities. The utility has a single WWTP. Table 51 summarizes the volume of liquid and sludge processed in the system.

Table 50: Annual Liquid and Sludge Volume Processed

Parameter	Units	2007	2006	2005	Average
Liquid Influent Volume	MG	24,000	29,000	28,000	27,000
Sludge Treated	MG	200	190	230	210
Sludge Solids Content[1]	%	5	5	5	5
Biosolids Produced[2]	wet tons	79,000	--	--	--
Liquid Effluent Volume[3]	MG	25,000	30,000	30,000	28,000

Notes:

[1] Sludge solids content reported is prior to treatment and dewatering.

[2] Biosolids is a term used to refer to treated end-products for disposal.

[3] Liquid effluent exceeds influent because a portion of treated water (~4-6% by volume) is trucked to the WWTP and is not registered by the influent flow meter.

The following sections describe the components of the case study system analyzed. Additional detail is available in Appendix H.2. The information has been obtained through the utility's website, publicly available publications, and communications with utility employees.

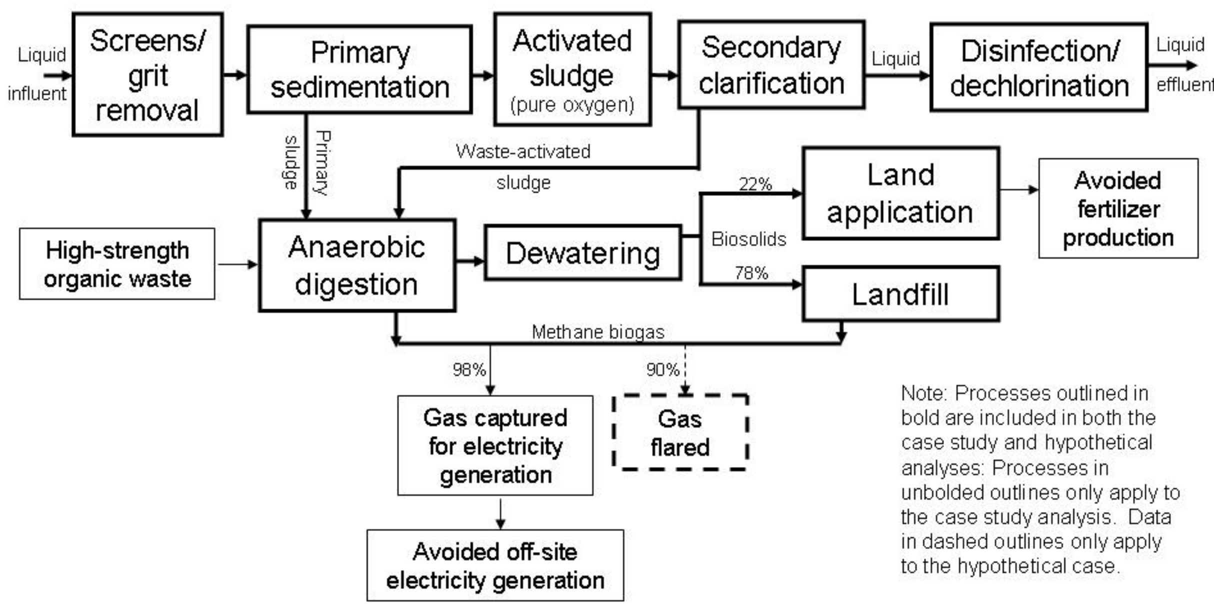
10.1.2.1 Collection Infrastructure Summary

The utility collects sewage from several contiguous communities. Some communities operate independent sewer systems which collect sewage from customers. The utility owns and operates infrastructure which collects sewage from these systems and transports it to the WWTP. Only utility-owned and -operated infrastructure is included in the analysis. A summary of the length and material of pipe in the collection system is in Appendix H.2. In addition, the collection system includes fifteen lift stations which house fifty pumps. Some facilities and/or pumps are only used in wet or dry weather. All the facilities and pumps are summarized in Appendix H.2.

10.1.2.2 Treatment System Summary

Treatment consists of two process streams: liquid and sludge treatment. The liquid treatment process includes coarse and fine screening, grit removal, primary sedimentation, pure oxygen AS, biological treatment, disinfection, and dechlorination prior to discharge. Sludge treatment includes thickening, anaerobic digestion, and centrifuge dewatering. Most of the treated biosolids (78 percent in 2007) are used as landfill alternative daily cover. The rest is land applied 130 miles away. Figure 31 shows a process diagram of the treatment process. Chemical consumption for liquid and sludge treatment are summarized in Table 52.

Figure 31: WWTP Process Diagram



Source: Stokes and Horvath 2011

Table 52: Annual Treatment Chemical Consumption

Chemical	Volume Consumed (1000 gal)	Delivery Distance (miles)	Tank Capacity (1000 gal)
Liquid Treatment			
Hypochlorite	3,800	560	200
Sodium Bisulfate	850	30	47
Ferric Chloride	250	30	12
Sludge Treatment			
Polymer #1	180	400	15
Polymer #2	200	3000	24

10.1.2.3 Discharge Infrastructure Summary

The utility discharges liquid effluent to a coastal outfall. The discharge piping includes 108-in. pipe on land. Wastewater is discharged through a 48- to 96-in. diffuser about 5,700 feet offshore.

10.1.2.4 Energy Consumption and Recovery Summary

Energy is consumed by the utility as electricity, natural gas, and diesel fuel. Table 53 summarizes the average electricity and fuel use between 2005 and 2007. In addition, the utility recovers energy by capturing CH_4 off-gas in its sludge treatment process and converting it to electricity. Additional high strength organic waste is added to the digesters to augment CH_4 production and, therefore, electricity generation. Energy recovery produced an average of 40,000 MWh annually over years 2005-2007.

Table 53: Annual Energy Consumption Summary

	Electricity MWh	Natural Gas therms	Diesel gallons
Collection[1]	1,500		500
Treatment[2]	42,300	100,000	31,910
Discharge	0	0	0

Notes:

[1] Values average energy consumption between 2005-2007.

[2] Treatment includes both liquid and sludge treatment.

10.1.2.5 Fleet Vehicle Use Summary

Vehicle operation was analyzed as well. The utility owns two maintenance trucks (Class 4 or higher), forty-seven smaller trucks (Class 2 or 3), and eight hybrid vehicles. Table 54 summarizes the average annual miles traveled and gas mileage for each category of vehicle.

Table 54: Fleet Vehicle Summary

	Total Annual Miles	Gas Mileage (mpg)
Truck (Class 2 or 3)	370,000	7.2
Truck (Class 4 or higher)	15,000	13.2
Hybrid Passenger Car	55,000	39.5

10.1.3 Hypothetical Case Study

A hypothetical system was also analyzed to assess the sensitivity of the results to particular design decisions in the case study utility. The hypothetical system and case study utility are identical except that CH_4 is captured from the treatment process at a rate of only 90 percent in the hypothetical, rather than the 98 percent capture rate from the case study utility. Also, CH_4 is not captured from the landfill and land application does not offset fertilizer production in the hypothetical case. This hypothetical system serves to quantify the benefits of these design decisions.

10.2 Task 10 Outcomes

The purpose of this task was to create a computer-based decision support tool, WWEST, which would allow wastewater utilities to conduct LCAs of their system design and operation, focusing on the energy requirements and air emissions due to energy consumption resulting from collecting, treating, and discharging wastewater and handling sludge wastes from the treatment process. WWEST was tested by analyzing a case study utility as well as a hypothetical system for sensitivity analysis. This analysis also includes the energy implications of material consumption and its supply chain, but decommissioning was not included because of lack of information. The emission and energy EFs for the case study and a similar hypothetical system are shown in Table 55. The results for the case study utility and the hypothetical system are discussed in the sections below. The conclusions are discussed in more detail in (Stokes and Horvath 2010), a link for which can be found in Appendix B.1. However, due to subsequent updates to the WWEST tool, the results themselves are not identical.

10.2.1 Case Study Results

As expected, the treatment phase dominates the results for both the utility and hypothetical system. The treatment phase contributes 94% percent of the energy consumption and 92% percent of the GHG results. The treatment phase contribution may be overstated because the analysis of the collection system is limited to infrastructure owned and operated by the utility. Some smaller collection pipelines are owned by the municipalities served by the utility. No information was collected about the physical extent of the collection system infrastructure or energy consumption for these municipalities.

However, the analysis of the treatment system is also limited. Due to time constraints and data availability, the utility did not provide a thorough inventory or costs for process equipment prior to the task deadline. The authors were not granted a site visit to conduct their own detailed inventory. The process equipment inventory considered in the analysis includes: pumps, process basins and tanks, and estimates of piping, electrical, and control equipment needs based on known plant costs. Cleaning, mixing, and aerating equipment, centrifuges, and other equipment were excluded due to a lack of cost data necessary for EIO-LCA analysis. Though the contribution of both the treatment and collection systems are underestimated, the treatment system is still likely to dominate the results if the entire system were analyzed.

Depending on the environmental effect considered, either the construction or operation phase contributes most to the results. The operation phase is most important for energy use (90 percent), GHGs (83 percent), NO_x (72 percent), and SO_x (53 percent). Construction is more significant for PM (57 percent) and VOC (72 percent). The utility offsets considerable air emissions by capturing CH_4 from their treatment system and using it to generate electricity, reducing the operational impacts relative to other phases. The electricity produced offsets generation from less clean sources of electricity like fossil fuels. The maintenance and end-of-life phases are not significant contributors (less than 8 percent) to overall results.

Table 55: Wastewater Utility Energy Use and Air Emission Results

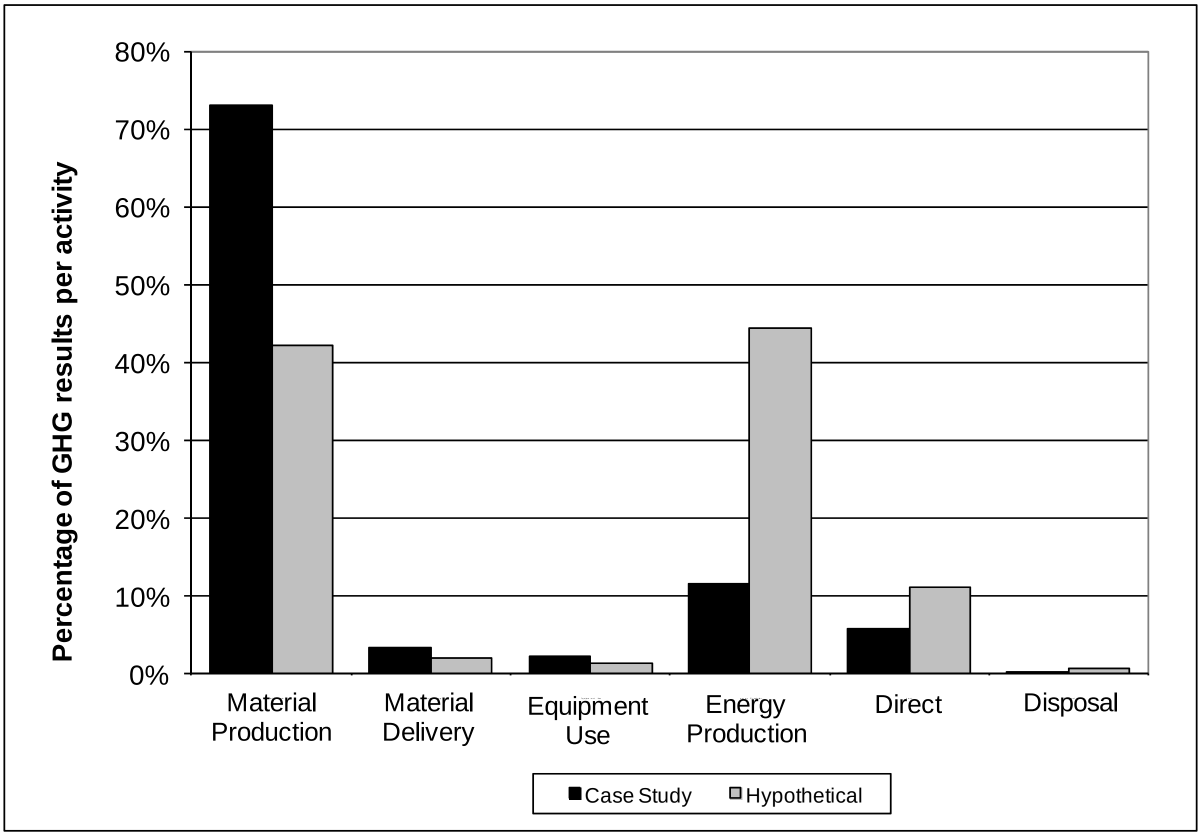
Results per ML (GJ energy, kg GHG, else g)	Energy	GHG	NO_x	PM	SO_x	VOC
Case Study						
Total	5.5	260	510	96	320	250
Wastewater Phase Results						
Collection	0.31	19	70	21	46	32
Treatment	5.2	240	440	74	270	220
Discharge	0.0082	0.67	2.1	0.41	1.7	1.3
Life-cycle Phase Results						
Construction	0.51	39	130	55	140	180
Operation	5.0	211	370	45	170	63
Maintenance	0.041	3.4	8.4	7.3	7.5	4.5
End-Of-Life	-0.0053	5.9	2.4	-0.74	-0.027	2.2
Activity Results						
Material Production	3.0	190	330	66	250	200
Material Delivery	0.31	9.0	120	16	7.6	26
Equipment Use	0.086	6.1	26	3.5	6.8	16
Energy Production	2.1	30	27	10	60	11
Direct	--	15	--	--	--	--
Disposal	0.0030	1.1	2.5	0.55	0.35	2.4
Hypothetical Results						
Total	7.0	450	640	130	790	340
Wastewater Phase Results						
Collection	0.33	21	74	23	51	36
Treatment	6.7	430	560	110	735	300
Discharge	0.0082	0.67	2.1	0.41	1.7	1.30
Life-cycle Phase Results						
Construction	0.52	42	140	58	150	190
Operation	6.2	400	400	58	630	130
Maintenance	0.26	10	95	19	13	22
End-Of-Life	0.0030	0.010	2.7	0.55	0.35	2.4
Activity Results[1]						
Energy Production	3.50	200	150	46	520	95
Direct	--	50	--	--	--	--
Disposal	0.0030	3.0	2.5	0.55	0.35	2.4

Note: Numbers may not sum due to rounding.

[1] Material Production , Material Delivery, and Equipment Use results are unchanged from the case study results.

The case study results indicate that material production is a bigger contributor than energy production for the utility for all environmental effects. This was not true for the water systems analyzed in prior phases of work and was unanticipated. In those cases, energy production dominated material production consistently. Figure 32 illustrates the GHG activity results for both the case study and the hypothetical system.

Figure 32: Greenhouse Gas Emissions by Activity



The largest contributors to material production results are chemicals, followed by reinforced concrete. Again, the effects of material production are relatively higher because of the energy production offsets at the treatment plant. In addition, the 25-year analysis period used for this study may exaggerate the contribution of materials with long service lives, including reinforced concrete which may be used for 100 years or more.

Direct CH_4 emissions from the treatment process contribute 6 percent to the overall GHG results, or 15 kg per ML. The utility's aggressive gas recovery program prevents these emissions from being a more significant contributor to the overall results. However, these emissions would have been dwarfed by electricity production emissions if not for the offsets from CH_4 combustion.

Material delivery contributes appreciably to the emissions of NO_x, PM, and VOCs (24 percent, 17 percent, and 10 percent, respectively). The material delivery effects are primarily due to sodium hypochlorite, a chemical used for disinfectant and manufactured 600 miles from the utility site. Equipment use contributes less than 7 percent to all environmental effects. Disposal contributes 1 percent to GHG emissions and less to other environmental effects. Biosolids which are land applied (78 percent of the disposed material) typically decompose to CO_2 which is excluded from the results as a biogenic source. The authors assumed the landfill, where the remaining biosolids are disposed, has a landfill gas recovery system (85 percent capture rate) that prevents significant GHG emissions.

These results quantify the energy use and GHG in a more comprehensive way than will be required by California's GHG reporting law. AB-32 will likely require utilities to report the direct emissions from their treatment process as well as the smokestack emissions from their electricity and other energy providers; this study includes the supply chain in energy production results. The GHG emissions reported for this utility for direct emissions and energy production, assuming the California state average electricity mix is applicable, would be approximately 38 kg per ML, compared with 45 kg per ML when the life-cycle energy effects are included. The overall life-cycle GHGs results, including material production, material delivery, equipment use and disposal effects, would be 260 kg.

10.2.2 Hypothetical System Results

Similar to the case study utility, the treatment phase is the primary contributor to environmental effects, contributing 90 to 96 percent for the hypothetical system. The percentages are higher than for the utility result because of the increase in energy production and direct emissions (uncaptured CH_4) from the treatment process. The limitations of the case study analysis also apply to the hypothetical system.

Among life-cycle phases, the operation phase is more significant for the hypothetical system than for the utility. The operation phase is a bigger contributor than the construction phase for all environmental effects except VOC. Construction phase contributes 45 percent of PM emissions.

The end-of-life phase GHG emissions are approximately six times higher for the hypothetical system. It was assumed that the landfill used by the hypothetical system does not recover the CH_4 emitted. Methane has a high global warming potential (GWP) and therefore has a greater impact on the results than landfill gas which is converted to CO_2 by flaring.

The hypothetical systems results indicate that energy production is more important than material production for the utility for energy use and GHG emissions; the reverse is true for other emissions. For energy use, 43 percent of the consumption is from material production and 50 percent from energy production. Material and energy production comprise 42 percent and 44 percent of GHG emissions, respectively.

Energy production is more important for the hypothetical system than the utility because they do not offset energy consumption with CH_4 gas recovery for electricity generation. Also, because the gas recovery system is less efficient, the direct CH_4 emissions from the hypothetical treatment plant are higher, 50 kg of CO_2(e) per ML compared with 15 kg for the utility, comprising 11 percent of total emissions.

Material delivery contributes appreciably to the NO_x emissions (19 percent). For other air emissions, the effects are less than 12 percent of the overall results. The results are explained by chemical delivery, as described in the Utility results section. Equipment use contributes less than 5 percent to all environmental effects. Disposal contributes less than 2 percent.

If the assumed California GHG reporting requirements are used, the GHG emissions reported for this utility for electricity production and direct process emissions, assuming the California state average electricity mix is applicable, would be approximately 180 kg per ML, compared with 250 kg when the life-cycle energy effects are included. The overall life-cycle GHGs results, including material production, material delivery, equipment use and disposal effects, would be 450 kg. For this utility, the reported value would only capture less than half of the overall GHGs associated with the wastewater processing.

10.3 Task 10 Conclusions and Recommendations

The conclusions of this task are divided into those related to WWEST, the case study analysis, and general conclusions.

10.3.1 WWEST

In the current form, WWEST has limitations, e.g., it does not assess all environmental emissions, account for ecological effects, or quantify environmental impacts such as human toxicity. Though the assessment of sustainability for wastewater systems is not complete, it does fill a gap by allowing utilities to capture an element of environmental sustainability that has been previously ignored.

The researchers' goal was to create a tool that was more user-friendly than WEST. However, the time spent creating macros and other special features to ease data entry traded off with time needed to analyze all aspects of wastewater treatment and processing. WWEST does not analyze all potential wastewater treatment processes but emphasizes the processes most commonly used at this time. The time frame of the project did not allow for complete evaluation of all of these issues. In the future, the authors would like to complete calculations to allow users to compare unit processes within the treatment plant.

Generally, utilities, designers, and system planners are not assessing the environmental effects of their systems using LCA for decision-making. For a more comprehensive picture of the costs for wastewater choices, LCA using WWEST or similar methodology should be conducted routinely to allow the industry to develop a comprehensive list of design recommendations for systems of differing parameters (e.g., scale, water quality, process selection).

WWEST should be introduced to utilities to educate them about the tools themselves and, perhaps more importantly, about life-cycle thinking. Such training was part of Task 8 within this contract. LCA should be encouraged for design and planning of new wastewater systems, expansions and retrofits. Utilities should be encouraged to take a long-term and life-cycle perspective on energy use and environmental emissions, including indirect emissions associated with the supply chain.

10.3.2 Case Studies

The data obtained from the case study utility were limited by availability for the utility and time constraints for data collection. It did not include inventory and cost information for much of the auxiliary equipment. In addition, information about portions of the collection system was not obtained from the municipalities that own and operate them. The results are useful and informative despite the limitations.

Some wastewater treatment processes allow opportunities for heat and energy recovery which can offset fossil fuel consumption and prevent GHG emissions. Anaerobic treatment processes which produce CH_4 are particularly good candidates. In the case study utility, the plant is able to meet approximately 90 percent of its electricity needs using captured CH_4. The utility plant's GHG was 190 kg per ML less than the potential emissions from the hypothetical plant.

Chemical delivery was a major contributor to NO_x emissions primarily because sodium hypochlorite, the disinfectant used in large volumes, is transported from a manufacturer located 600 miles away. The assumed delivery vehicle was a long-distance truck. A closer source of this chemical would reduce the overall environmental effect of the system.

Disposal choices are also a place where utilities have some control over their life-cycle environmental effects. For the case study system, it was assumed that disposal alternatives offset fertilizer use if land applied and were used for electricity generation if landfilled. Neither was assumed to be the case for the hypothetical system. The disposal choices of the utility prevented 2.9 kg of GHG per ML.

The indirect effects associated with material production may be more important for wastewater processes than for water systems. These should be evaluated carefully by wastewater professionals.

Greenhouse gas recovery can greatly affect the overall environmental burden of a WWTP. Using methane to generate electricity further reduces the environmental burden by offsetting less-clean energy sources like fossil fuels.

Disposal choices may also be important for a wastewater system that wants to limit its environmental burden. Offsets with fuel or electricity consumption or generation as well as other materials (e.g., fertilizers) can be important to limiting the system's effect on the environment.

10.3.3 General

Several factors, including economic, engineering, and policy concerns, typically influence wastewater design decisions. Heretofore, the comprehensive and system wide 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.

This task expands prior 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, including analyzing additional wastewater treatment processes. The results of this study can be used to target future research in areas where improvements to the wastewater treatment systems can be made most readily.

CHAPTER 11:
Task 11 – Evaluate Decentralized Water and Wastewater Systems

Decentralized water and wastewater treatment have been proposed as strategies to reduce potable water consumption (Nelson 2005) and an energy-efficient alternative to more centralized treatment systems. Decentralized treatment systems are defined as the collection, treatment, and distribution of water and wastewater near the point of use or generation (Crites 1998) and have the flexibility to be tailored to local conditions and demands. These systems reduce the infrastructure and energy for collection and distribution through shorter transport distances. The reduced flow volumes associated with decentralized systems can also allow for the use of smaller diameter piping, shallower installation depths, and vacuum and pressurized sewers (Nelson 2005), all of which have the potential to reduce energy and material use. Decentralized wastewater systems also create the opportunity for effluent reuse by locating treatment adjacent to areas with high demands for non-potable water, such as golf courses and public landscaping, thereby redirecting large volumes of water back into the urban water supply (Allen and Vonghia 2005). While a wide range of treatment processes are available to decentralized systems, the inherent loss in economies of scale relative to more conventional centralized treatment has the potential to increase the energy, cost, and materials associated with facility operation. Comparing the cost and benefits between centralized and decentralized water and wastewater treatment requires expanding the evaluation scope beyond the facility operation to determine how design decisions impact each stage of the treatment process. A proper environmental analysis and comparison of decentralized treatment systems must account for the materials and energy consumed, and the pollutant released, during the collection, treatment, and distribution process, as well as account for water and wastewater treatment avoided through water reuse and gray water separation strategies available with decentralized treatment.

11.1 Task 11 Approach

WEST and WWEST produce a system-wide life-cycle comparison of centralized and decentralized water and wastewater treatment systems. Additional modifications were made to the tools to allow for analysis of common decentralized treatment technologies. Case studies of potential decentralized water and wastewater treatment systems were developed and detailed based on currently operating systems and readily available technologies. The modified tools were applied to the identified case studies to show how the tools can be used to evaluate the environmental effects of the decentralized systems, including relative energy consumption and related air emissions, of the different phases of the water supply system (collection, treatment, and discharge), life-cycle phases (construction, operation, maintenance, end-of-life), and specified activities (material production, material delivery, equipment use, energy production, sludge disposal, and direct emissions).

11.1.1 Revisions

As part of this task, WEST and WWEST were revised to allow customized analysis of distributed water and wastewater treatment facilities. The completed WEST and WWEST revisions included adding the capability to assess MBRs and analyze septic tanks and UV disinfection.

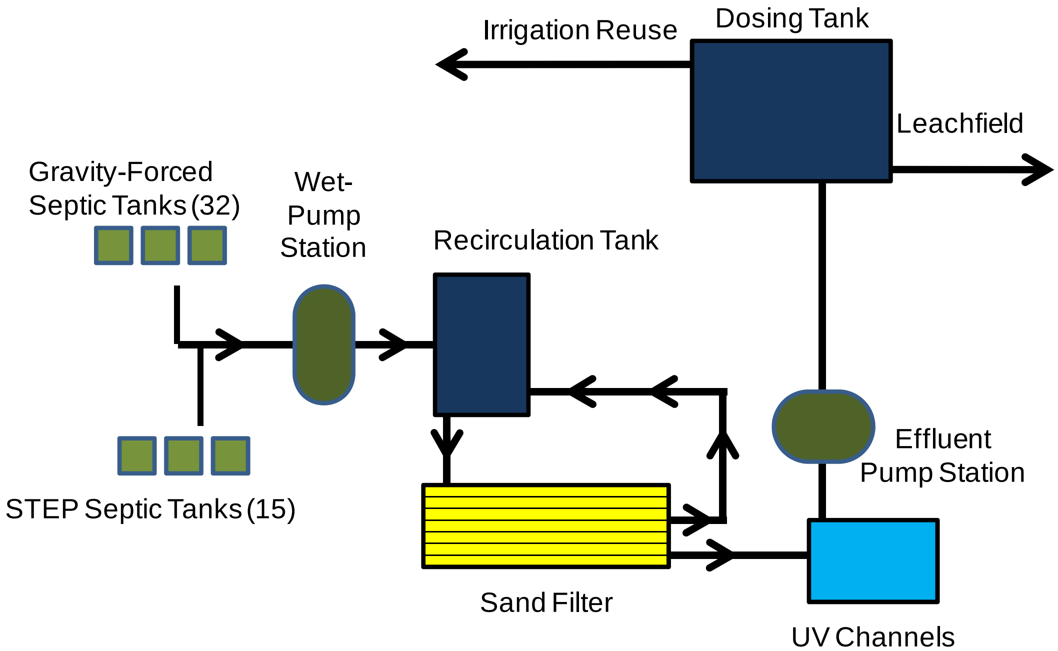
11.1.2 Case Studies

Case studies of potential decentralized water and wastewater treatment systems are based on currently operating systems and readily available technologies. Two decentralized wastewater treatment case studies are defined; one based in the Stonehurst community of Martinez, California and another based on a small MBR treatment plant in Corona, California.

11.1.2.1 Stonehurst Septic Tank Decentralized Wastewater Treatment

Stonehurst is a 47-lot subdivision located in a suburban community outside of San Francisco, CA. The wastewater treatment system at Stonehurst has operated since the early 1990s and has been described as a successful and innovative decentralized wastewater treatment strategy for California (Crites et al 1997). The details of this wastewater treatement system have been outlined in previous publications (Crites et al 1997; Tchobanoglous et al. 2003).. The treatment system was designed to treat about five million gallons per year (GPY) and treats an average of about three million GPY. Each house lot in Stonehurst uses onsite septic tank systems, which is a well established wastewater treatment technology that is commonly used in rural communities and found in nearly 25 percent of homes nationally (USEPA 2005). Effluent from onsite septic systems is typically distributed to an adjacent drainfield for aerobic treatment, requiring a large amount of open space. The footprint for the septic tanks systems at the Stonehurst homes is reduced through a community wastewater collection system that transports the septic tank effluent for nearby treatment and reuse. Each home contains a 1500 gallon concrete septic tank that is connected to a two-inch diameter sewer main located along the development roadway. Thirty-two of the homes are located uphill of the roadway and connect to the sewer main through small diameter gravity-forced piping. The other 15 homes are downhill of the roadway and each has a small 0.33-hp septic tank effluent pump (STEP) to transport wastewater to the sewer main. Approximately 3.25 miles of sewer-main piping connect the homes to a single wet-pump station that uses two 2-hp pumps to transport the effluent to a community treatment plant. The treatment plant consists of a recirculating sand filter, where the wastewater is first sent to a recirculating tank and then pumped through a two-ft gravel bed approximately five times before being sent across a three open channel UV supply sump for disinfection. An effluent pump station then transports the treated water to a 3000 gallon hilltop dosing tank, where the water distributed to a 2.5-acre community soil absorption field. Treated water in the dosing tank is also reused as irrigation through a subsurface drip system for a small nearby park. Figure 33 presents a schematic of the decentralized wastewater treatment system in the Stonehurst development.

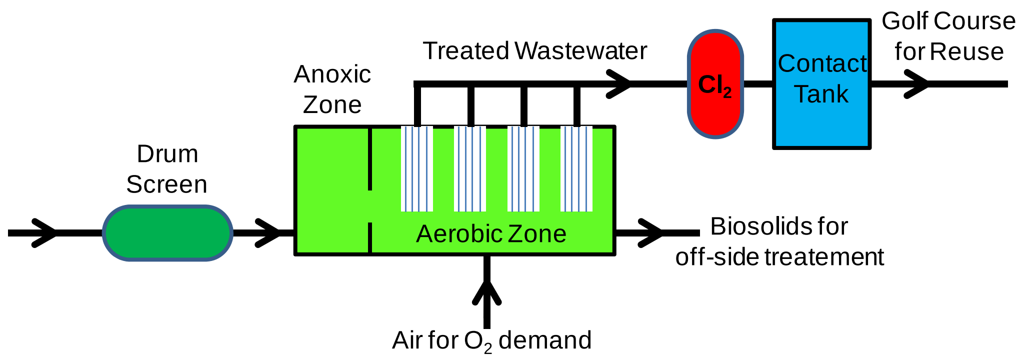
Figure 33: Decentralized Wastewater Treatment System for the Stonehurst Case Study



11.1.2.2 Corona MBR Decentralized Wastewater Treatment

While a relatively nascent wastewater technology, the small footprint and potentially high effluent quality of MBRs indicate the potential for strategically placing this type of treatment plant in locations that would benefit most from wastewater reuse (Allen and Vonghia 2005). MBRs replace the clarifier and sedimentation stages found in conventional WWTPs, reducing the plant size and operational requirements and allowing MBRs to be used for smaller and more decentralized purposes. Commissioned in 2001, the MBR WWTP in Corona, California treats an average daily flow of 1.1 MGD (General Electric 2008). Figure 34 presents a schematic of the Corona WWTP. Wastewater influent that reaches the plant is first pump to a rotary drum screen to remove grit and solids. The wastewater then enters a concrete tank that is divided into three process trains. Each process train contains an anoxic zone (for denitrification) that wastewater passes through before entering the aerobic zone (for BOD removal and nitrification) that houses the MBR. The Corona WWTP uses ZeeWeed 500 immersed membranes. The ZeeWeed 500 membranes consist of hollow fiber filters composed polyvinylidene fluoride (PVDF), a chlorine and oxidant-resisting polymer (Ortiz et al 2007). Pumps provide a negative pressure to force wastewater into the hollow fibers and across the membrane to separate biosolids from treated wastewater. Blowers bubble air throughout the aerobic zone to satify oxygen demand for BOD removal and for nitrification of influent ammonia concentrations. The treated wastewater is then chlorinated for disinfector and pumped to a contact tank before being pumped to Eagle Glen Golf Course reservoir for reuse.

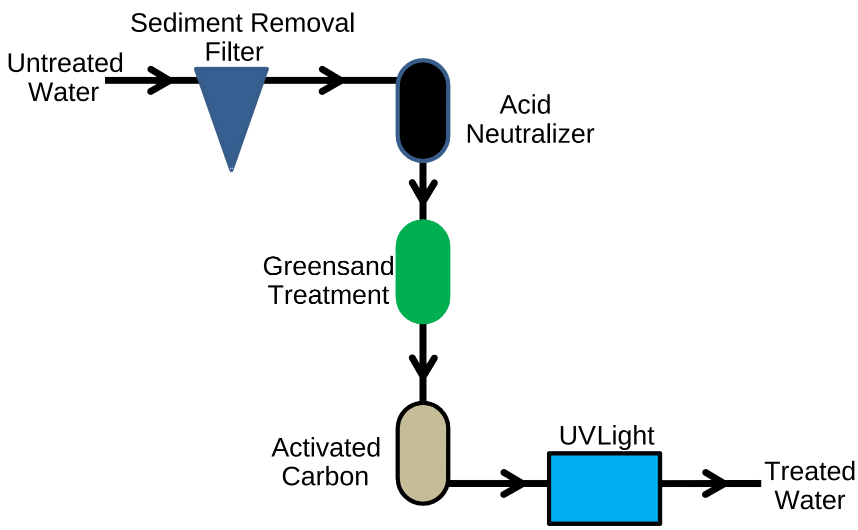
Figure 34: Decentralized Wastewater Treatment System for the Corona Case Study



11.1.2.3 Point-of-Use Water Treatment System

The case study for decentralized water treatment is designed using currently available point-of-source treatment technologies. The case study assumes untreated water (i.e., well water or untreated municipal water) being treated to drinking standards at the point-of-entry (POE) into a home or business. As shown in Figure 35, untreated water passes through a series of treatment filters before reaching the tap for use. First, the untreated water enters a sediment removal filter containing anthracite coal, calcined aluminum silicate and garnet to reduce the concentration of suspended solids. The pH of the water is then adjusted as the water passes through an acid neutralizer containing calcite and magnesia. A greensand treatment filter is used to remove iron, magnesium, and sulfur ions. Organic compounds are removed by an activated carbon filter. Finally, the water is exposed to UV light for disinfection before reaching the point-of-use tap within the building. The case study assumes this POE system treats 600 GPD; equivalent to the average water consumption for a family of four (AWWA 1999).

Figure 35: Point-of-Entry Water Treatment Case Study

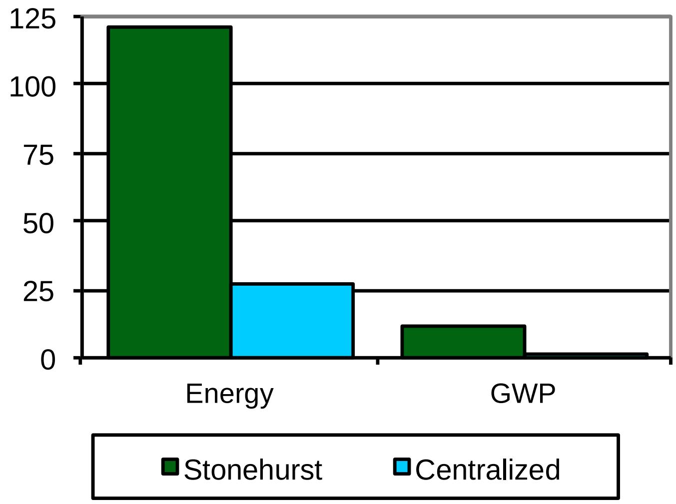


11.2 Task 11 Outcomes

11.2.1 Stonehurst Outcomes

Energy and GHG results for the Stonehurst decentralized wastewater system are presented in Figure 36. Energy use and GHGs for hypothetical centralized wastewater utility in California (see Chapter 10) are compared in Figure36. Figure shows the Stonehurst case study requires about five times more energy than the larger centralized system (labeled as "Centralized"). Specifically, the Stonehurst system uses about 125 GJ of energy for every MG treated wastewater while the Centralized system uses about 25 GJ. A similar magnitude difference is observed between the two treatment systems for GHGs, with one MG of treated wastewater at the Stonehurst site resulting 12 Mg of GHG emissions while only about 2 Mg are associated with the Centralized utility.

Figure 36: Energy and GHG Emissions Summary

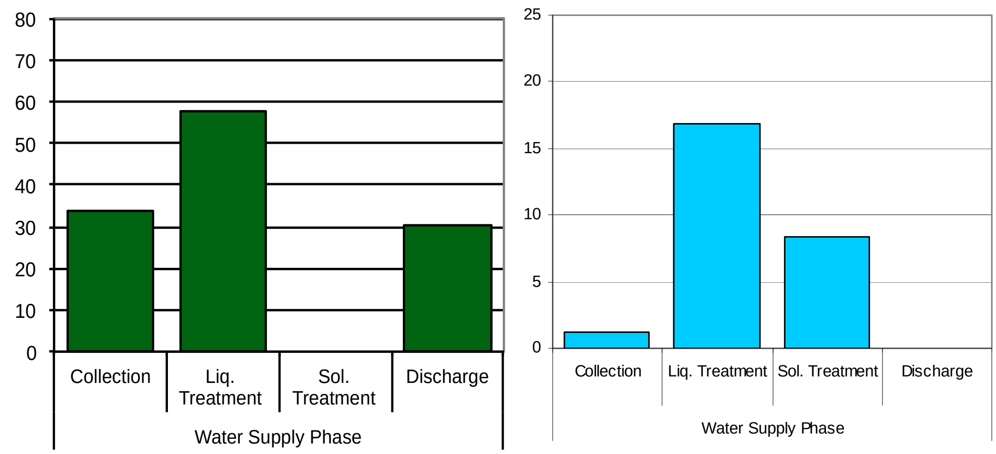


Values represent GJ for energy and Mg of GHGs per MG of treated wastewater.

Figures 37 - 39 disaggregate the WWEST energy results for both the Stonehurst and Centralized treatment system into wastewater phases, life-cycle phases, and activity, respectively. Separating energy use by wastewater phase, as shown in Figure 37, illustrates that treatment at Stonehurst represents about half of all energy use and the other half is divided between the collection and discharge phases. Collection and discharge of the water supply phase for the Centralized wastewater treatment, however, are relatively insignificant with treatment representing nearly all the energy use. While the low impact of collection and discharge may be due to economies of scale with such a large utility, this low impact may also be due to locally owned and operated collection infrastructure are not included in the Centralized case study

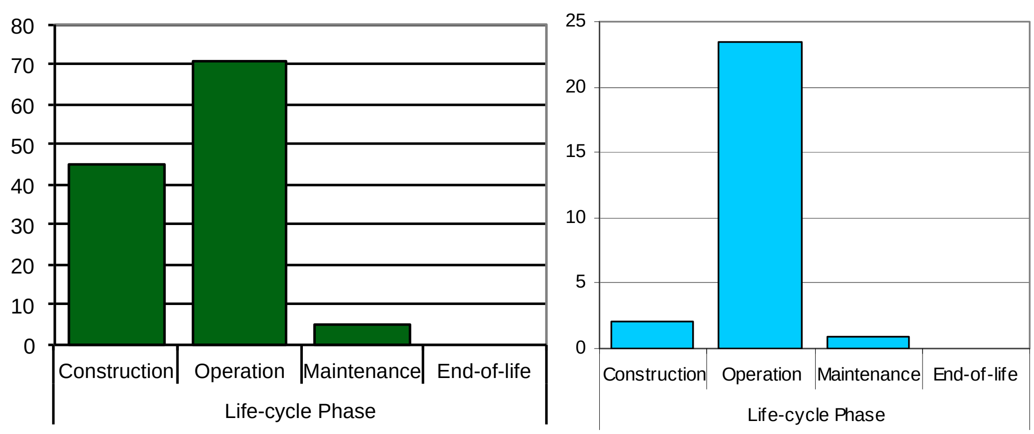
(Stokes and Horvath 2010). Figure 38 shows that operation demands the greatest amount of energy for both the Stonehurst and Centralized system. The energy associated with construction, and to a lesser extent maintenance, in the Stonehurst case study, however, is significant, while the operation phase represents nearly all energy use for the Centralized system. Figure 39 disaggregates energy use by activity and indicates that energy production (representing electricity generation) is the greatest contributor to the energy use for Stonehurst, followed by material production and equipment use. Figure 39 also shows that energy use for the Centralized system is fairly evenly divided between energy production and material production, while energy associated with equipment use is relatively minor.

Figure 37: Water Supply Phase Energy Use



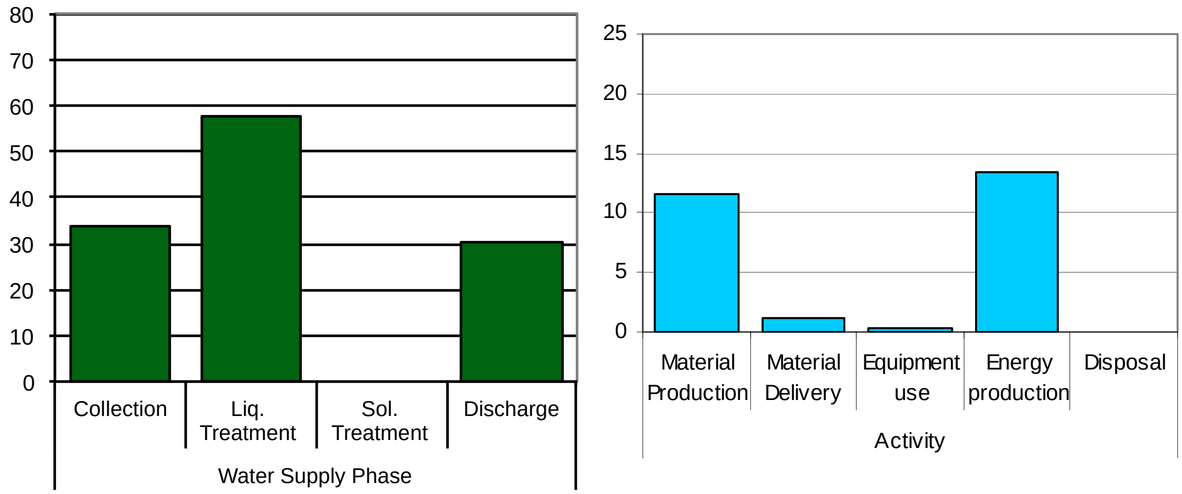
Energy use (GJ) per MG for Stonehurst (left) and centralized system (right). Note the difference in scale.

Figure 38: Life-Cycle Phase Energy Use



Energy use (GJ) per MG for Stonehurst (left) and centralized wastewater system (right). Note the difference in scale for Stonehurst and centralized treatment results.

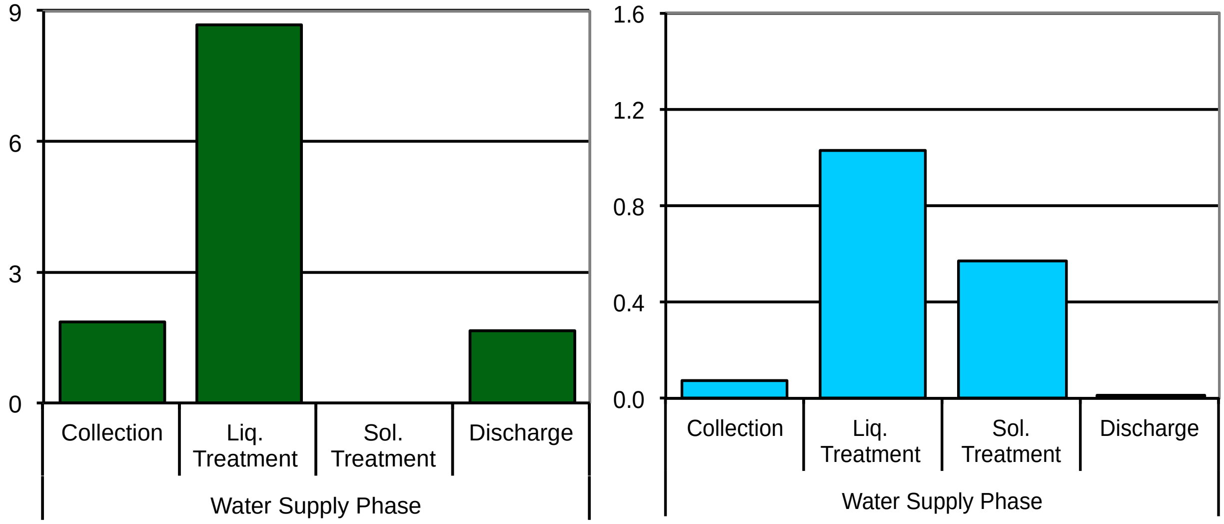
Figure 39: Activity Phase Energy Use



Energy use (GJ) per MG for Stonehurst (left) and centralized wastewater system (right). Note the difference in scale.

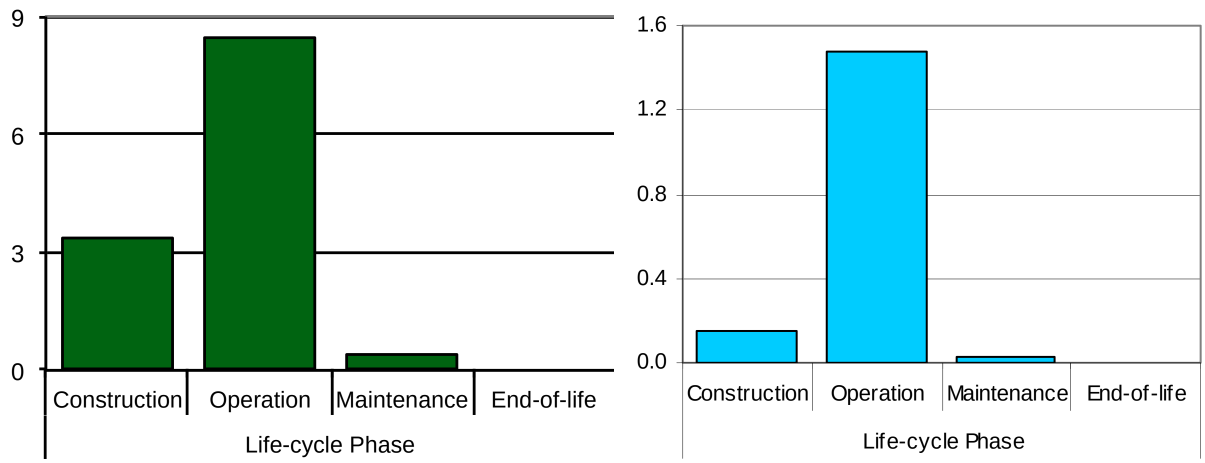
Figures 40 - 42 disaggregate the GHG emissions for the Stonehurst and Centralized systems into wastewater phases, life-cycle phases, and activities, respectively. Figure 40 shows the GHG emissions from liquid treatment at Stonehurst are greatest, though GHG emissions from collection, solid treatment, and discharge are still significant. Results for GHG emissions for the Centralized system show that liquid treatment accounts for nearly all of the GHG emissions. Figure 41 shows that the distribution of GHG emissions by life-cycle phase is fairly similar for both the Stonehurst and Centralized systems, with most emissions occurring during the operation phase. Figure 42, which separates GHG emissions by activity, shows that direct emissions account for nearly half of all the GHGs released from the Stonehurst system while direct emissions are a minor contribution for the Centralized system. This significant disparity is due to CH_4 released from the septic tanks and from solid disposal in the Stonehurst system. Alternatively, the CH_4 emissions from the centralized wastewater treatment plant occur at the treatment facility and are assumed to be effectively controlled (Stokes and Horvath 2010).

Figure 40: Water Supply Phase GHG Emissions



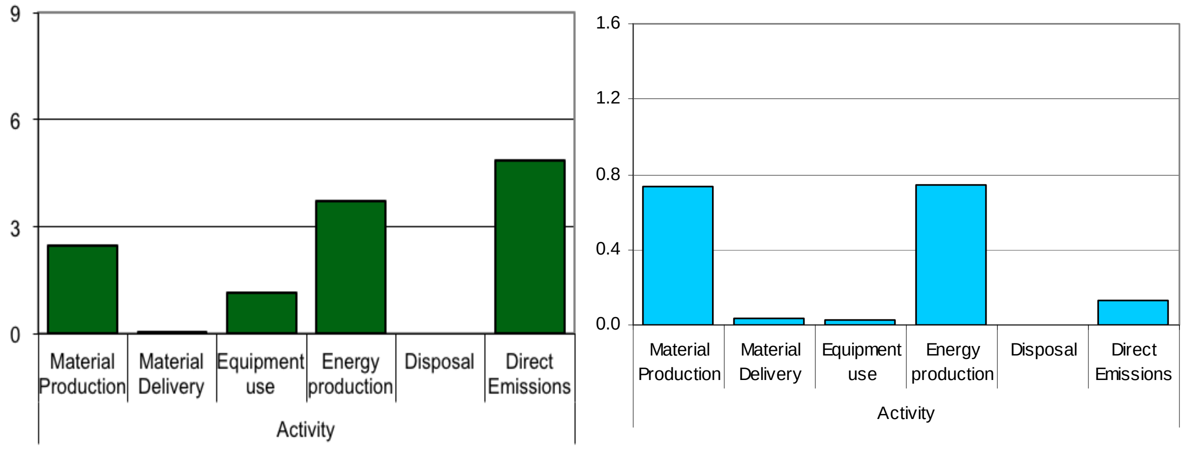
GHGs in Mg per MG for Stonehurst (left) and centralized system (right). Note the scale difference.

Figure 41: Life-Cycle Phase GHG Emissions



GHGs in Mg per MG for Stonehurst (left) and centralized system (right). Note scale difference.

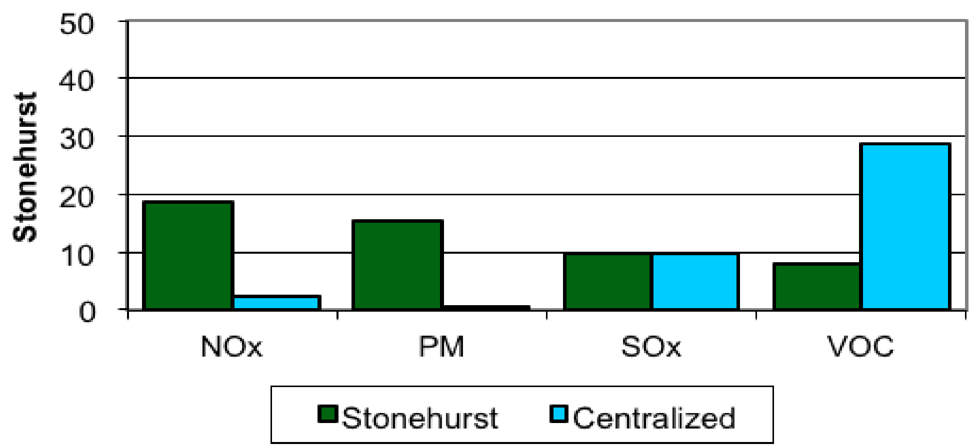
Figure 42: GHG Emissions by Activity



GHGs (Mg) for Stonehurst (left) and centralized system (right) per MG. Note the scale difference.

Figure 43 presents WWEST results for air pollutant emissions, specifically NO_x, PM, SOx, and VOC, from both the Stonehurst and the Centralized wastewater system. Similar to the energy and GHG results, the air pollutant emissions from wastewater treatment at the Stonehurst site are approximately an order of magnitude greater than the emissions from the Centralized system for a given functional unit. Along with the absolute difference between the two wastewater systems, the results also show a difference between the relative pollutant emissions. The relatively greater emissions of NO_x and PM at the Stonehurst site, compared to the Centralized system, indicate a greater impact from emissions associated tailpipe emissions from vehicles and equipment. The dominant NO_x and SO_x emissions at the centralized plant indicate that the majority of the air pollutants released are associated with electricity generation.

Figure 43: Air Pollutant Emissions Summary

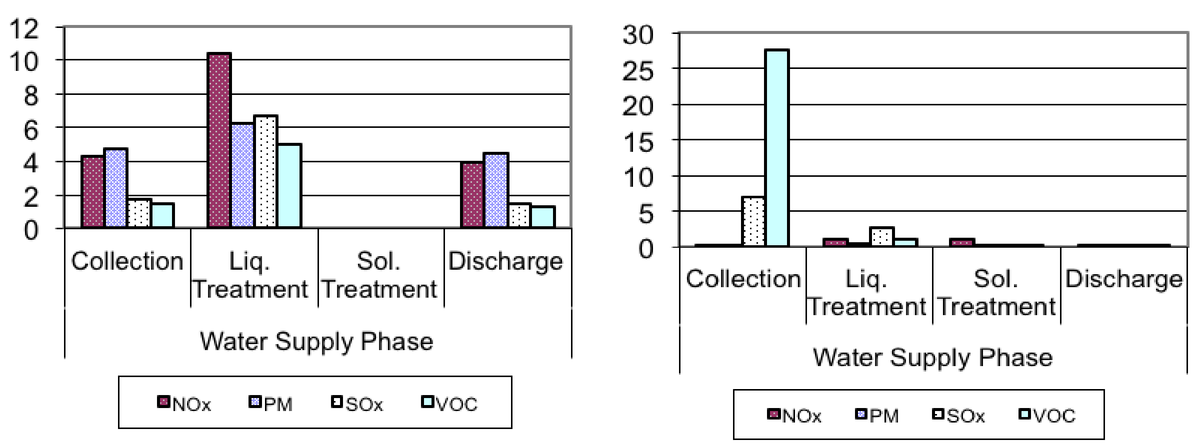


Air pollutant emissions for Stonehurst and centralized systems in kg per MG of treated wastewater.

Figures 44 - 46 disaggregate the WWEST air pollutant emission results for both the Stonehurst and Centralized treatment system into water supply phases, life-cycle phases, and activity, respectively. Figure 44 shows that the distribution of air pollutants among the collection, liquid treatment, and discharge phases at the Stonehurst site is similar in proportion to the energy use distribution in Figure 44. The relative emissions for each air pollutant are fairly equal for each water supply phase at the Stonehurst site. Results for the Centralized plant show that most of the air pollutants occur during treatment and that these pollutant emissions are dominated by NO_x and SO_x, indicating that the majority of these air pollutant emissions may be associated with electricity generation.

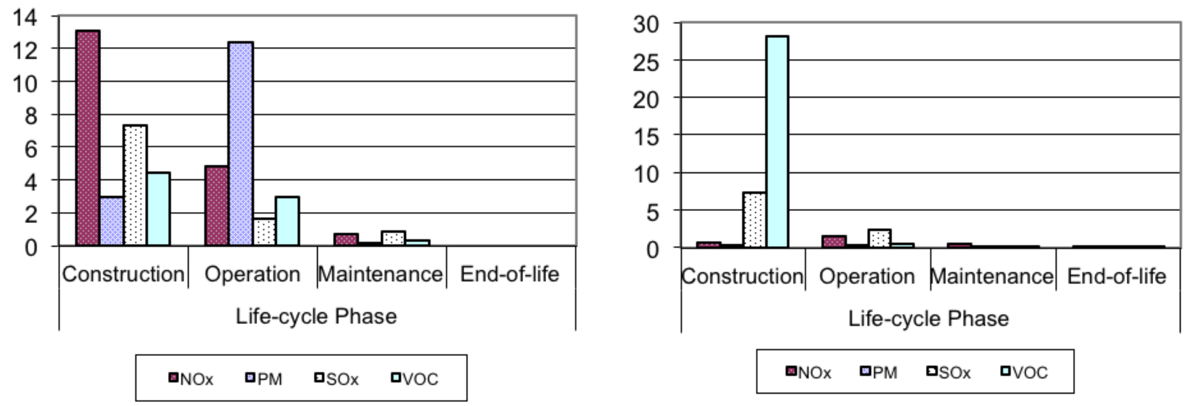
Figure 45 presents the distribution of air pollutants between different life-cycle phases and shows that most emissions occur during the construction and operation phases for both the Stonehurst and the Centralized plant. The distribution of air pollutants indicates that most of these emissions are associated with construction, though a significant amount of PM occurs during the operation phase. The relative emission for both the construction and operation phase at the Centralized plant are indicative of emission associated with electricity production. Figure 46, shows that significant PM emissions at the Stonehurst site occur during energy production. Along with energy production, air pollutant emissions are primarily associated with material production for both the Stonehurst and Centralized systems. Air pollutants emissions, specifically NO_x, are also significant from equipment use in the Stonehurst system.

Figure 44: Water Supply Phase Air Pollutant Emissions



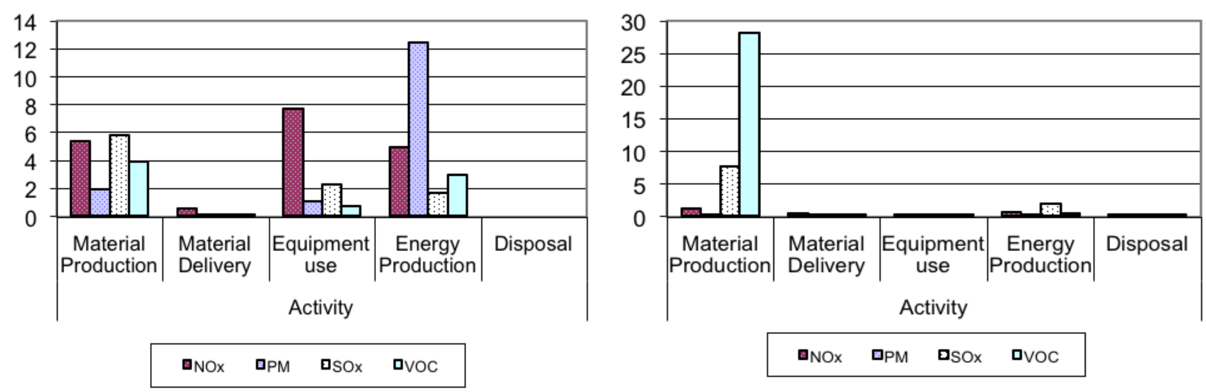
Air pollutant emissions (kg per MG) for Stonehurst (left) and centralized system (right). Note the difference in scale for Stonehurst and centralized treatment results.

Figure 45: Life-Cycle Phase Air Pollutant Emissions



Air pollutant emissions (kg per MG) for Stonehurst (left) and centralized system (right). Note scale difference.

Figure 46: Air Pollutant Emissions by Activity



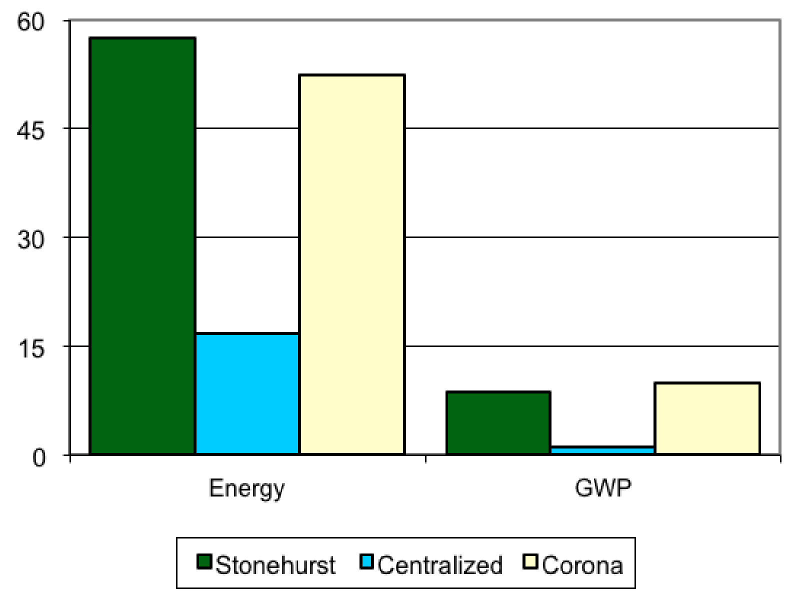
Air pollutant emissions (kg per MG) for Stonehurst (left) and centralized system (right). Note the difference in scale.

11.2.2 Corona Outcomes

Energy and GHG results for the Corona MBR treatment plant are presented in Figure 47. These results represent only the treatment phase of the wastewater treatment process (i.e. results do not include collection or disposal). Figure 47 compares energy consumption and GHG emissions of the Corona MBR treatment with the wastewater treatment phase at the Centralized plant (conventional process train) and at Stonehurst. The calculations show that the MBR treatment in the Corona case study consumes 52 GJ for every MG of treated wastewater, which is similar to the 57 GJ required at Stonehurst but more than the 17 GJ needed at the Centralized system. A similar trend is observed when comparing the treatment phase of each case study for

GHGs, with one MG of treated wastewater resulting 10 Mg, 1 Mg, and 9 Mg of GHG emissions for the Corona, Centralized, and Stonehurst case studies, respectively.

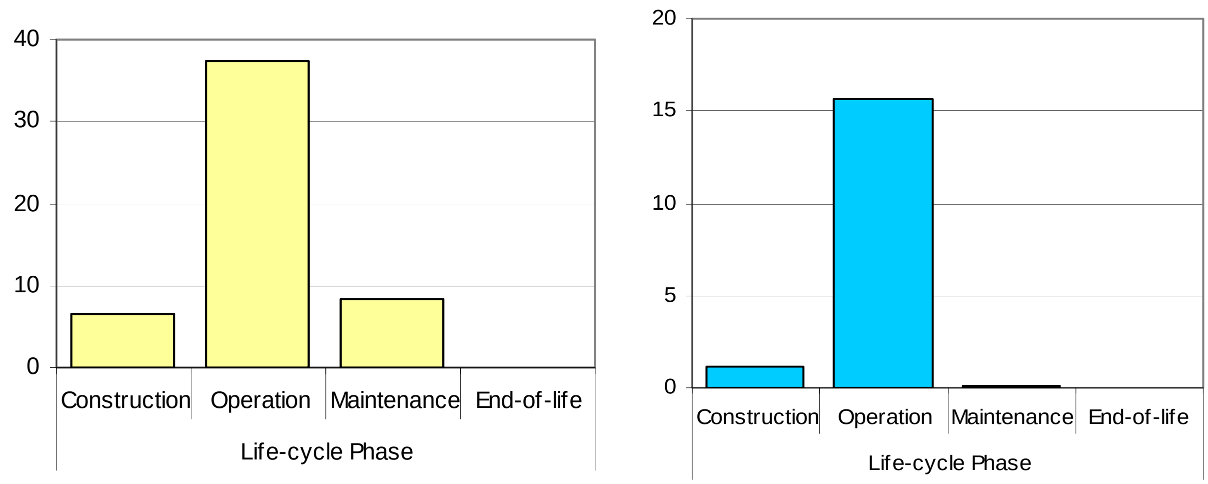
Figure 47: Treatment Phase Energy and GHGs Summary



Energy (GJ) and GHG (Mg) per MG comparison of the treatment phase of the Stonehurst, Centralized, and Corona systems.

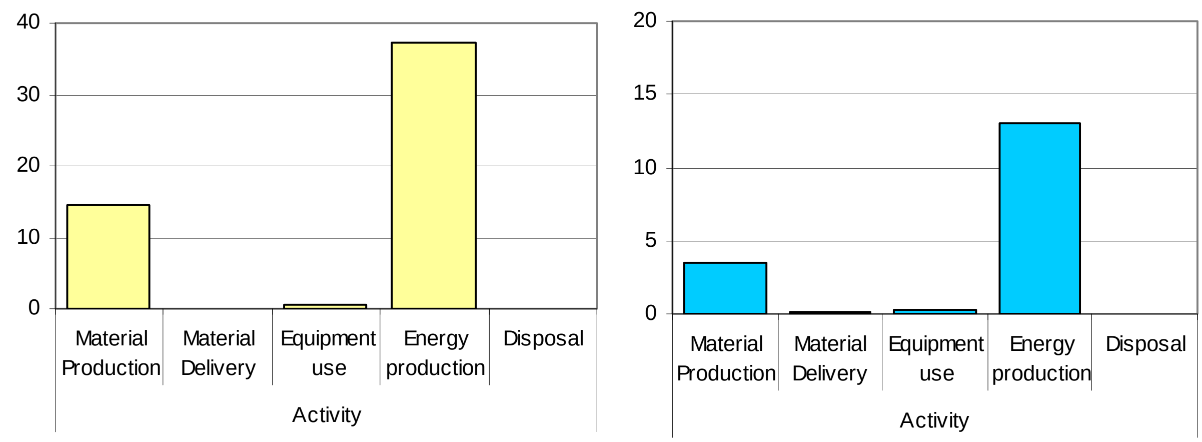
Figures 48 and 49 disaggregate the WWEST treatment phase energy results for both the Corona and Centralized treatment systems into life-cycle phases and activity, respectively. Figure 48 shows that operation stage demands the greatest energy for both the Corona and Centralized systems. The energy associated with construction and maintenance at the Corona plant, however, is still significant, while the operation phase represents nearly all energy use for the Centralized treatment process. Figure 49 disaggregates treatment phase energy use by activity and indicates that energy and material production together require nearly all of the energy consumed throughout the lifecycle for the Corona case study, while material delivery, equipment use, and disposal are relatively nominal. This distribution of lifecycle energy is also observed for treatment phase energy use at the Centralized system.

Figure 48: Life-Cycle Phase Energy Use



Treatment energy use (GJ per MG) of the Corona (left) and Centralized system (right). Note the difference in scale.

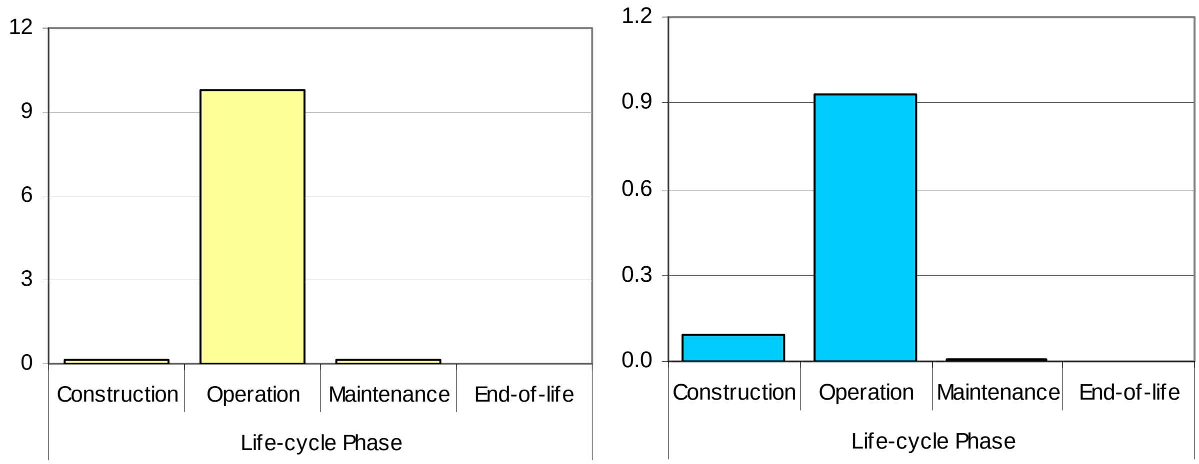
Figure 49: Activity Phase Energy Use



Treatment energy use (GJ per MG) of the Corona (left) and centralized system (right). Note the difference in scale.

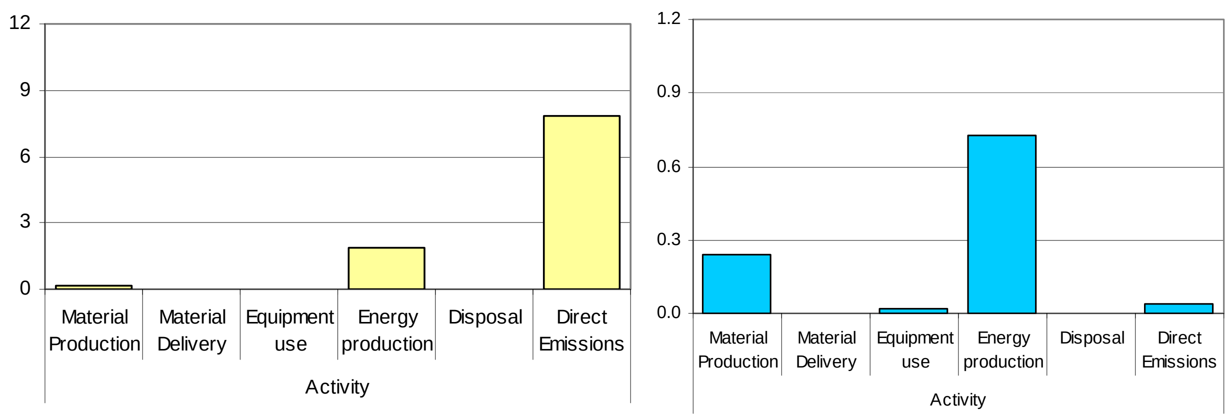
Figures 50 and 51 disaggregate GHG emissions for treatment at the Corona and Centralized treatment systems into life-cycle phases and activity, respectively. Figure 50 shows that the distribution of GHG emissions by life-cycle phase is similar for wastewater treatment at both the Corona and Centralized plant, with most emissions occurring during the operation phase. Figure 51, which separates GHG emissions by activity, shows that direct emissions account for more than half of all the GHGs released at the Corona plant while direct emissions are a minor contribution to the treatment phase emissions for the Centralized system. While CH_4 emission are effectively controlled at the Centralized plant (Stokes and Horvath 2010), the large amount of direct emissions in the Corona case studyare the result of assuming no methane flaring at this small MBR plant.

Figure 50: Life-Cycle Phase GHG Emissions



GHGs (Mg) per MGfor the treatment phase of the Corona (left) and centralized (right) wastewater system. Note the order-of magnitude difference in scale for Corona and Centralized results.

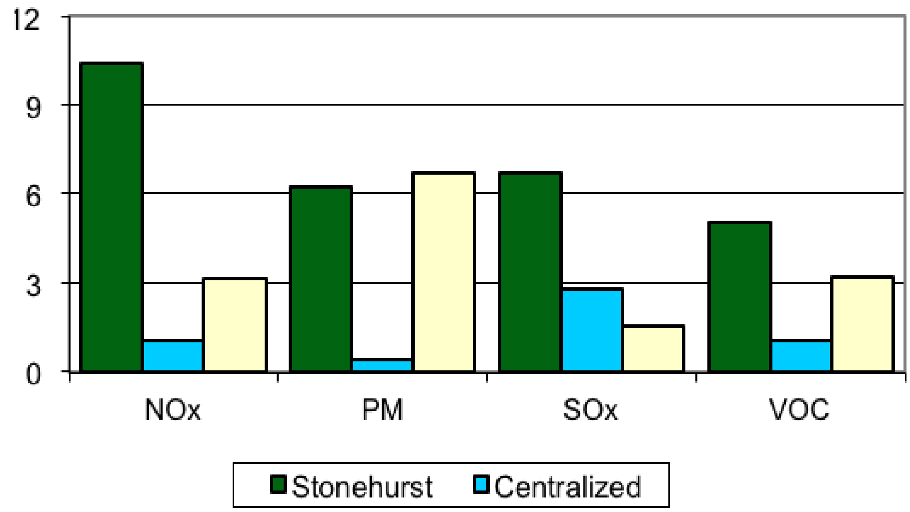
Figure 51: GHG Emissions by Activity



GHGs (Mg) for the treatment phase of the Corona (left) and centralized (right) system. Note the order-of magnitude difference in scale for Corona and Centralized treatment results.

Figure 52 presents WWEST results for air pollutant emissions, specifically NO_x, PM, SO_x, and VOC released during the treatment phase for both the Corona and the Centralized WWTPs. The air pollutant emissions at the Corona and the Centralized plants are comparable, with the Corona emissions slightly higher for each of the pollutants except SO_x. Stonehurst treatment emissions are considerably higher than the other case studies for all air pollutants calculated.

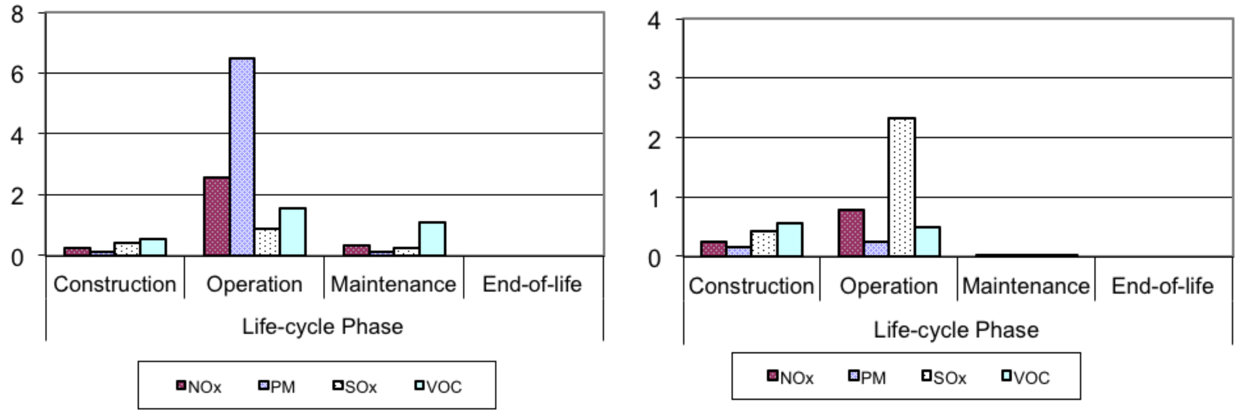
Figure 52: Treatment Phase Air Pollutant Emissions Summary



Air pollutant emission (kg) per MG comparison of the treatment phase of the Stonehurst, Centralized, and Corona treatment systems.

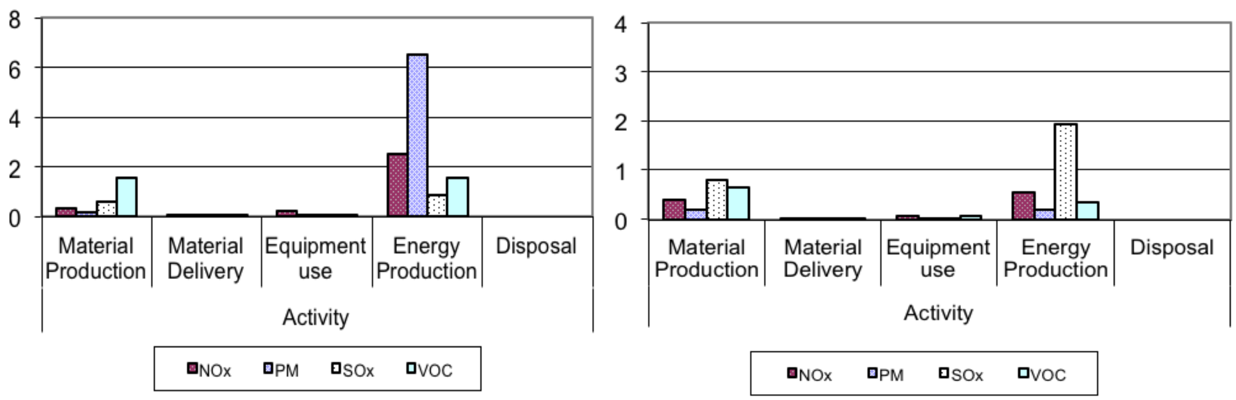
Figures 53 and 54 disaggregate the WWEST air pollutant emission results for the treatment phase at both the Corona and Centralized treatment plants into life-cycle phases and activity, respectively. Figure 53 presents the distribution of air pollutants between life-cycle phases. At the Corona plant most PM, SO_x, and NO_x emissions occur during the operation phase. VOC emissions are fairly evenly distributed among the construction, operation, and maintenance life-cycle phases. SO_x emissions at the Centralized plant mostly occur during operation. Similar emission levels of the other air pollutants at the Centralized plant occur between the construction and operation phases. Figure 54, shows that the PM, SO_x, and NO_x emissions are the result of electricity generation. The treatment air emissions at the Centralized plant are relatively low and similarly distributed among the energy and material production activities.

Figure 53: Life-Cycle Phase Air Pollutant Emissions



Air pollutant emissions (kg) per MG for the Corona (left) and Centralized (right) WWTPs. Note the difference in scale for Corona and Centralized treatment results.

Figure 54: Air Pollutant Emissions by Activity

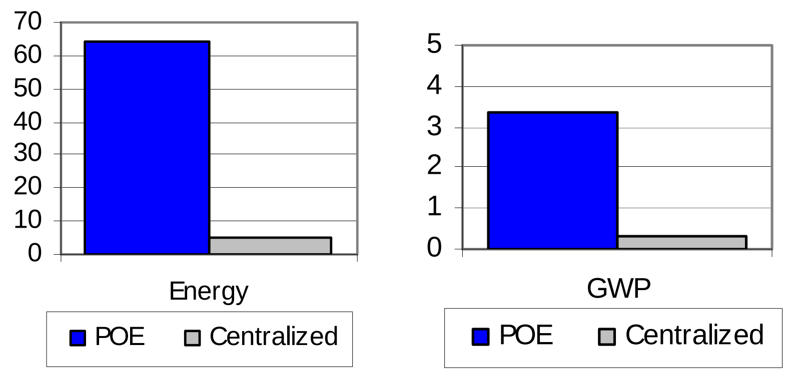


Air pollutant emissions (kg) per MG for the Corona (left) and Centralized (right) WWTPs. Note the difference in scale for Corona and Centralized treatment results.

11.2.3 Point-of-Entry Outcomes

Energy and GHG results for the POE water treatment case study are presented in Figures 55a and 55b. These results represent only the treatment phase (i.e. results do not include supply or distribution. Figures 55a and 55b also present, for comparison, the energy consumption and GHG emissions from the water treatment at a large centralized water treatment utility in California (Stokes and Horvath 2011; see Chapter 9). The calculations show that the POE water treatment consumes 65 GJ for every MG of treated water, which is considerably greater than the 5 GJ needed at the Centralized system. A similar trend is observed when comparing the water treatment from each case study for GHGs, with one MG of treated water resulting 3 Mg of GHG emissions for the POE water treatment case study while the Centralized system emits an order of magnitude less, 0.3 Mg.

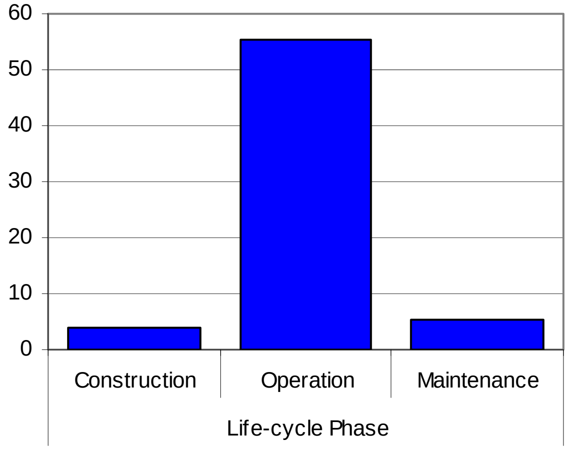
Figure 55a and 55b: Water Treatment Energy and GHGs Summary

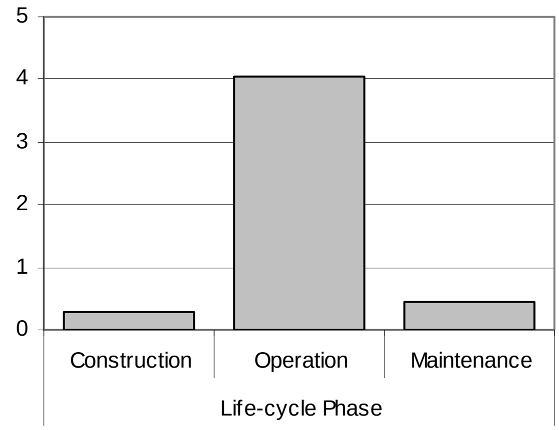


Energy (MJ) and GHGs (Mg) per MG comparison for a POE and Centralized water treatment system. Note the scale difference.

Figures 56 and 57 disaggregate the results for water treatment of both the POE case study and Centralized treatment plant into life-cycle phases and activity, respectively. While the overall energy use is significantly greater in the POE case study, Figure 56 shows a similar relative distribution of energy use among the life-cycle phases for both the POE and Centralized systems, with the majority of energy use occurring during operation. Figure 57 disaggregates energy use by activity and indicates that energy production (representing electricity generation) is the greatest contributor of the energy use for the POE case study, with this electricity demand primarily due to UV disinfection. Figure 57 also shows that material production energy for the Centralized system is fairly equal to the energy production, due to the relatively large amount of energy required in the production of treatment chemicals.

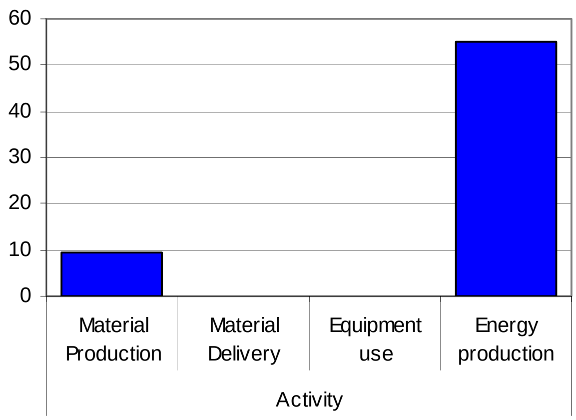
Figure 56: Life-Cycle Phase Energy Use

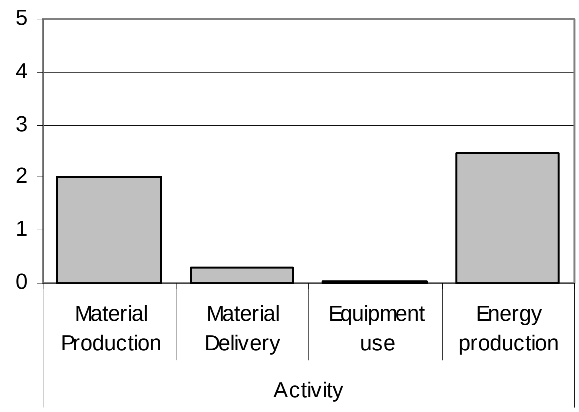




Energy use (GJ) per MG of the POE case study (left) and Centralized system (right).Note the difference in scale.

Figure 57: Activity Phase Energy Use



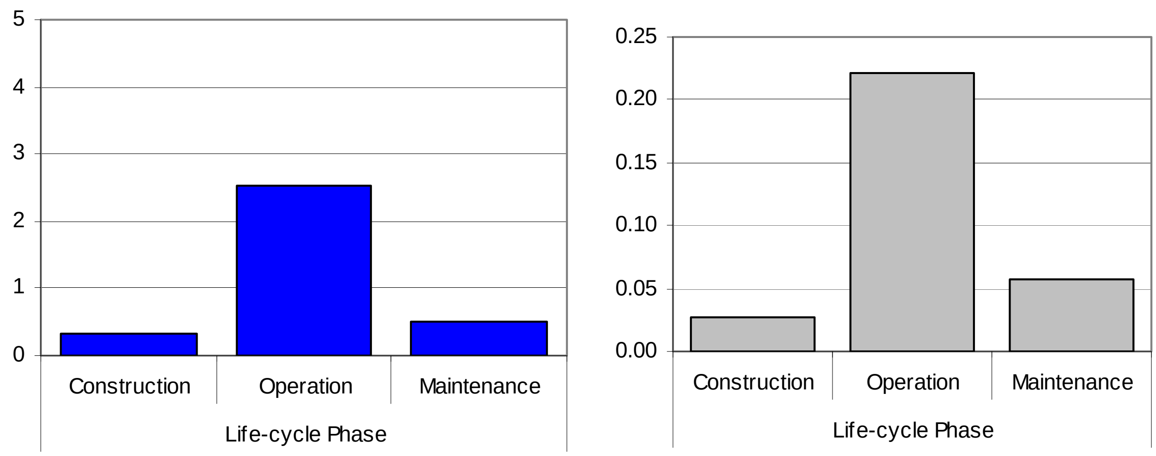


Energy use (GJ) per MG of the POE case study (left) and Centralized water treatment system (right). Note the scale difference.

Figures 58 and 59 disaggregate the GHG results for both the POE case study and Centralized water treatment systems into life-cycle phases and activity, respectively. Figure 58 shows that GHG emissions follow a similar trend to the life-cycle phase disaggregated energy use in Figure 56, with most GHG emissions occurring during operation for both the POE and Centralized water treatment systems. Figure 59, which separates GHG emissions by activity, shows that emissions generated during material production become significant relative to the GHG emissions from energy production for the POE system, and GHG emissions from material production are actually greater than the GHG emissions from energy production for the Centralized system.

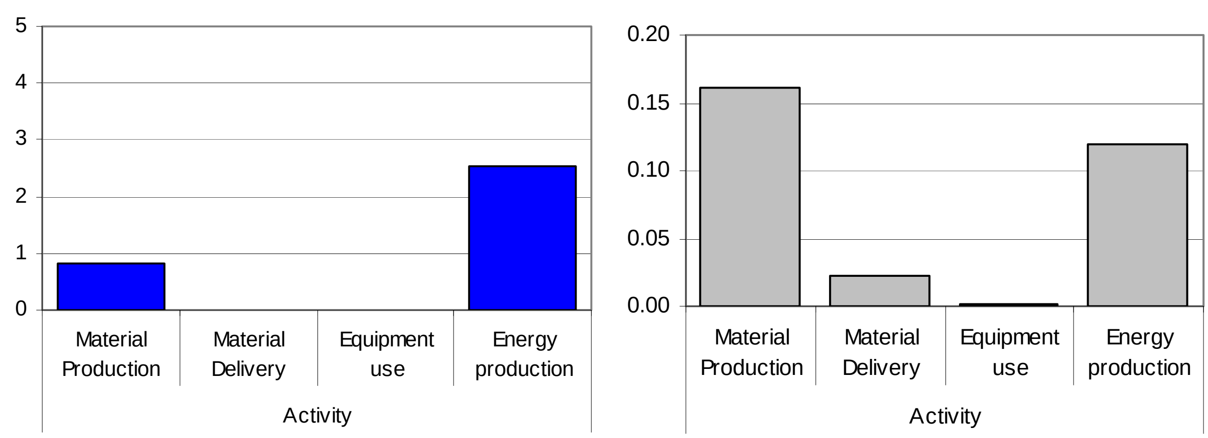
Figure 60 presents results for air pollutant emissions, specifically NO_x, PM, SO_x, and VOC, from both the POE case study and Centralized treatment systems. The air pollutant emissions from the POE case study are greater than the emissions from the Centralized treatment facility, though to a lesser extent than observed with the energy and GHG results. Along with the absolute difference between the two water treatment systems, the results also show a difference between the relative emissions of the pollutants. The relatively greater emissions of SO_x for the POE case study indicates the dominant contribution of electricity generation, while the relatively large VOC emissions in the Centralized system is a result of the production of certain treatment chemicals (primarily ammonia and sodium hydroxide).

Figure 58: Life-Cycle Phase GHG Emissions



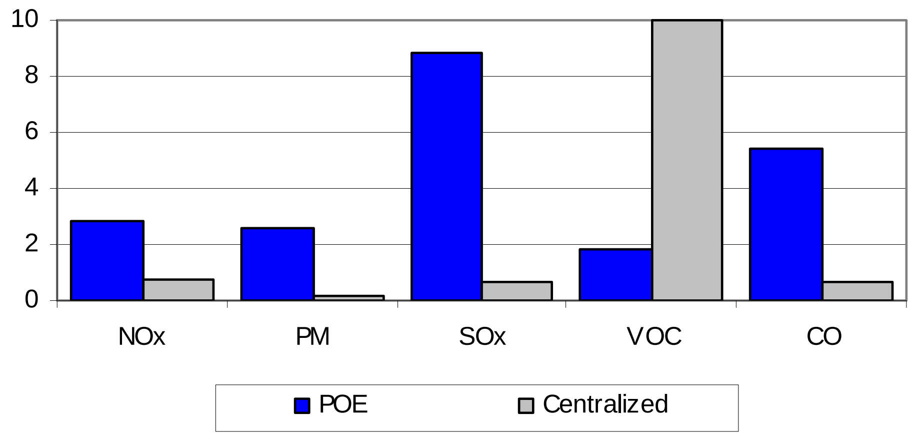
GHGs (kg) per MG for the POE case study (left) and Centralized water treatment system (right), separated by life-cycle phase. Note the difference in scale for POE and Centralized treatment results.

Figure 59: GHG emissions by Activity



GHGs (kg) per MG for the POE case study (left) and Centralized water treatment system (right). Note the difference in scale.

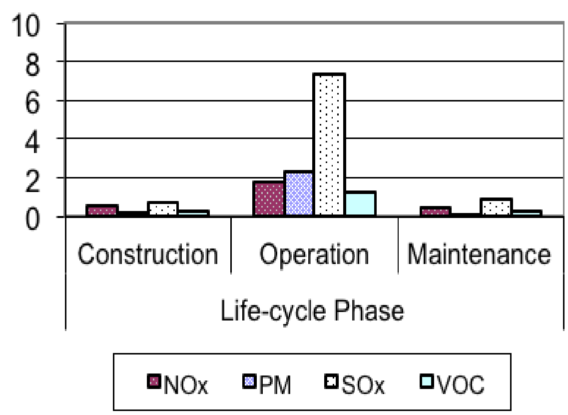
Figure 60: Water Treatment Air Pollutant Emissions Summary

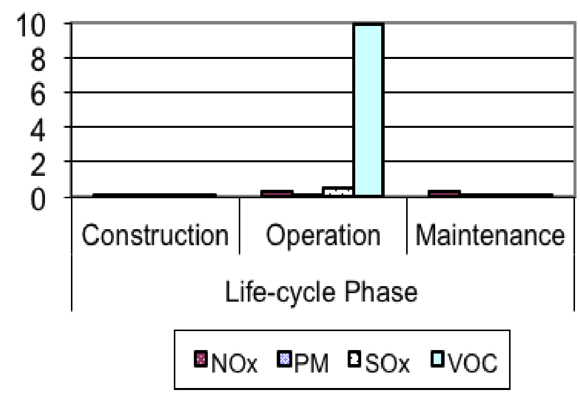


Air pollutant emissions (kg) per MG comparison of the POE case study and Centralized water systems.

Figures 61 and 62 disaggregate the air pollutant emissions for both the POE and Centralized systems into life-cycle phases and activities, respectively. The distribution of air pollutants between different life-cycle phases confirms that most emissions occur during the operation phase for both the POE case study and Centralized plant. The distribution of air pollutants for the POE case study indicates that most of these emissions are associated with material and energy production during operation while the relatively significant amount of VOC with the Centralized plant confirms that these emission are the result of producing chemicals used in the during the operation.

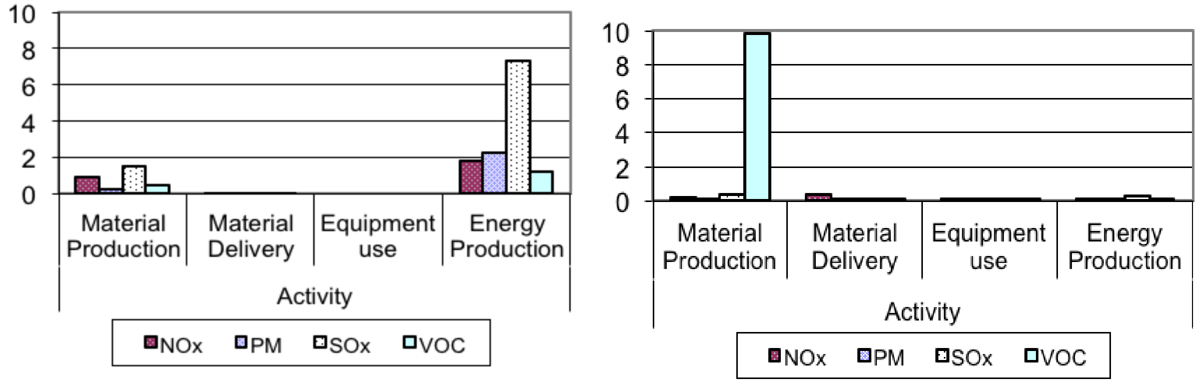
Figure 61: Life-Cycle Phase Air Pollutant Emissions





Air pollutant emissions (kg) per MG for the POE case study (left) and Centralized water system (right). Note the difference in scale for POE and Centralized treatment results.

Figure 62: Air Pollutant Emissions by Activity



Air pollutant emissions (kg per MG) for the POE case study (left) and Centralized water treatment system (right). Note the difference in scale for POE and Centralized treatment results.

11.3 Task 11 Conclusions and Recommendations

Energy, GHG, and air emissions from three wastewater treatment case studies were evaluated using the WWEST model. Results show that the economies of scale with Centralized plant outweigh the impact benefits gained from both the low energy (Stonehurst) and high technology (Corona) decentralized case studies. The Centralized facility also benefits from flaring methane generated during the treatment process while CH_4 was assumed to be directly emitted in the decentralized systems.

The WEST model was used to compare energy, GHG, and airemissions from a POE case study and a centralized water treatment facility. The results indicate that the economies of scale associated with a Centralized facility result in lower energy use and emissions. While Centralized water treatment impacts are normalized across a large volume of water, POE system only treats household water demand. Furthermore, most of impacts from the POE system are fixed regardless of variation in household demand so that conservation efforts, at the household level, would provide minimal benefit. The results show that energy and emissions associated with the POE case study are primarily due to energy production required for the operation UV lighting. Alternative forms of POE disinfection may reduce the environmental impact on household water treatment.

CHAPTER 12: Project Summary

This chapter summarizes the project MR-06-08, completed between October 15, 2006 and December 31, 2010. The project consisted of eleven tasks:

- Task 1: Administration. Consisted primarily of tracking project activities, documenting, reporting, communicating with the Energy Commission, and budgeting over the project period.
- Task 2: Assess alternative energy sources. Edited WEST to allow the user to enter customized electricity mixes.
- Task 3: Consider additional water sources. Revised the tool to be used to analyze any water source or alternative scenario.
- Task 4: Calculate EFs for common materials. Evaluated the life-cycle emissions for common material choices in water systems, including pipe materials and tank design.
- Task 5: Include life-cycle effects of electricity generation. Updated WEST to allow the user to analyze California water systems using life-cycle EFs for electricity production.
- Task 6: Evaluate demand management measures. Quantified the effects of reducing water demand through conservation programs.
- Task 7: Consider additional pollutants. Expands the pollutants analyzed to include additional air emissions as well as water and land pollutants.
- Task 8: Develop workshops for industry professionals. Involved planning and presenting WEST and WWEST to industry professionals during two workshops, one in Southern California and one in Northern California.
- Task 9: Improve material production analysis. Provided more detailed analysis of certain materials not well-defined using EIO-LCA (the tool choice in Phase One of the project), especially chemicals and plastics. Data were obtained from publicly- and commercially-available sources.
- Task 10: Analyze the energy demand of wastewater systems. Created a separate decision support tool, WWEST, and evaluated a case study system.
- Task 11: Evaluate decentralized water and wastewater systems. Updated WEST and WWEST to evaluate decentralized water and wastewater case studies.

Each task is described in detail in a preceding chapter. This chapter provides some combined context for the outcomes from the various tasks and case studies that were part of this project.

12.1 Project Outcomes

The following describes the outcomes of the overall project, including a summary of major deliverables and outcomes from the case study analyses.

12.1.1 Deliverables

Table 56 summarizes the deliverables for the project, including which task or tasks are associated and where the deliverable can be located. Future updates to the tools and documentation will be available at http://west.berkeley.edu/model.php.

Table 56: Project Deliverables

Task(s)	Deliverable	Location	Notes
2, 3, 5, 7, 9	Revised WEST Tool	Appendix A.1.1	The tool was revised several times throughout the project duration & was submitted with project Progress Reports as each task was due. The final version is included herein.
	WEST Documentation	Appendices A.1.2, A.1.3, A.1.4	The appendix includes the user manual, revision log, & copies of the explanatory/help worksheets.
2	Desalination Comparison	Chapter 3	The case study analyzes a hypothetical desalination system in Coastal California.
3	Northern California Case Study Report	Chapter 4	The authors reanalyzed the results of a Phase One Northern California utility, including reservoir water that provides the majority of the utility's water supply but was previously excluded.
4	WESTLite Tool	Appendix E.1	The WESTLIte tool analyzes which piping material & tank design are environmentally preferable to establish baseline EFs for common uses of these materials in water supply.
	WESTLite Documentation	Appendix E.2	The appendix includes the Explanatory/Help worksheets from the WESTLite tool.
	Planning guidelines for common materials	Chapter 5	The outcomes for Task 4 include tables which describe which common materials are environmentally preferable under various conditions (e.g., pipe diameter, tank capacity).
5	Northern & Southern California Case Study Report	Chapter 6	The researchers reanalyzed Phase One utilities (NC-Current, NC-Proposed, & SC) including the life-cycle effects of electricity generation & sludge disposal.
6	Comparison of conservation & water supply	Chapter 7	The outcomes compared results from the NC-Proposed water supply option to conservation programs (i.e., indoor & outdoor options for residential & other customers).
7	Desalination Results Report	Chapter 8	A hypothetical scenario for providing desalinated water to California's major cities was analyzed using the updated WEST.
8	Workshop Materials	Appendix G	The appendix includes copies of the slides for two workshops, one in Northern & one in Southern California.
9	Case Study Results	Chapter 10	The authors analyzed two additional case studies in Northern California, one small & one large.
10	WWEST Tool	Appendix A.2.1	The final version of WWEST is included in the appendix.
	WWEST Documentation	Appendices A.2.2, A.2.3, A.2.4	The appendix includes the user manual, revision log, & copies of the explanatory/help worksheets.
	Wastewater utility case study results	Chapter 11	A large wastewater utility was analyzed using WWEST. This utility captures methane to produce electricity to run their plant. A typical hypothetical utility was analyzed for comparison.
11	Decentralized Water & Wastewater Case Study Results	Chapter 12	Two decentralized wastewater scenarios were analyzed. One uses septic tanks followed by secondary treatment. The other incorporates membrane bioreactors (MBRs). One residential point-of-entry water system was also analyzed.

12.1.2 Water System Case Studies

After all the revisions were made to WEST, the researchers reanalyzed all case studies collected up to that date using the same analysis parameters. The functional unit was one Ml and the analysis period was 25 years. All case studies were then compared on an equal basis to see better how different utilities and water sources performed using LCA. Table 57 summarizes these utilities and water sources analyzed.

Table 57: Project Case Study Summary

			Sources (%)					
System	**Location**	**Production (Mℓ/year)**	**Imported**	**Local surface water**	**Ground-water**	**Brackish Desal**	**Seawater Desal**	**Recycled**
NC-Small	Northern California	6700			100%			
NC-Current	Northern California	38000	26%	72%				2%
NC-Proposed	Northern California	38000		72%			26%	2%
SC	Southern California	41000	92%			8%		<1%
NC-Large	Northern California	280000	95%	5%				

Note: The electricity consumption values for the NC-Current and NC-Proposed systems were analyzed using the revised electricity consumption values discussed in Task 3 (see Chapter 4.) The SC recycled water electricity values were similarly revised using estimates from (Energy Commission 2005).

Table 58 shows the energy, GHG, and NO_x results for each of the five case study utilities described above, assuming the water source mix shown in Table 58.

Table 58: California Utility Results Summary

Utility	**Energy (GJ/Mℓ)**	**GHGs (Mg/Mℓ)**	**NO_x (Mg/Mℓ)**
NC-Small	20	1.4	0.0035
NC-Current	6.4	0.32	0.00045
NC-Proposed	16	0.83	0.00083
SC	16	0.75	0.00086
NC-Large	5.6	0.33	0.00089

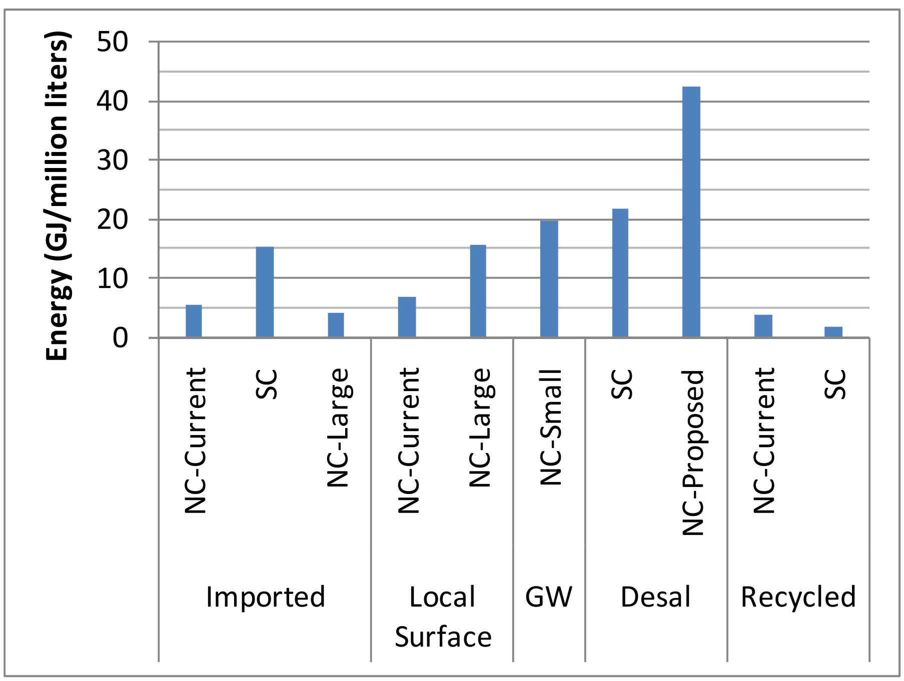
On a systemwide basis, the NC-Small utility consistently results in higher environmental burden, more than twice the other systems in most cases. Two factors may contribute to this outcome: 1) the significant amount of electricity needed to pump groundwater, the sole source of water for this system; or 2) economies of scale. The other analyzed utilities all produce more than five times the water produced in the NC-Small case. Groundwater energy use is primarily related to water depth and will vary significantly based on site conditions.

The NC-Proposed and SC case studies showed similar results. NC-Proposed implements a seawater desalination which is energy intensive, though it only makes up 26 percent of the water supply. SC, on the other hand, uses a less-intensive form of desalination, brackish groundwater, for 8 percent of their supply. However, the majority of SC's water is imported through the SWP and CRA, both energy-intensive sources.

The NC-Current and NC-large utilities have the lowest environmental effects, according to this analysis. NC-Current primarily uses local surface water combined with imported water that does not require much treatment. NC-Large imports most of its water (95 percent) but the aqueducts are gravity-fed, making it an energy-efficient water source.

Figure 63 compares the energy results for all the water sources evaluated independently. This figure confirms the conclusions described above. The NC-Small groundwater results are comparable to SC's brackish groundwater system. NC-Proposed's desalination system results in twice the energy use of any other source.

Figure 63: Comparison of Energy Demand of Various Water Sources



Recycled water is shown to be environmentally preferable in both of the systems analyzed. However, it is not significantly better than the NC-Large's imported water. However, not all environmental effects are included in the results. Notably, the impacts of water withdrawal on ecological receptors (e.g., habitat) or on long-term source sustainability (i.e., ensuring recharge is equal to or greater than withdrawals) are not included. Including these ecological effects would likely penalize all results except recycled water.

12.1.3 Wastewater System Case Studies

Energy, GHG, and pollutant emissions from three wastewater treatment case studies were evaluated using the WWEST model. Results from WWEST in Tables 59 and 60 show that the economies of scale with Centralized wastewater treatment outweigh the impact benefits gained from both the low energy (Stonehurst) and high technology (Corona) decentralized wastewater treatment case studies.

Table 59: Wastewater Case Study Summary

Results	Centralized	Stonehurst
Energy (GJ)	26	122
GHG (Mg)	2	12
No_x (kg)	2	19
PM (kg)	0	15
SO_x (kg)	10	10
VOC (kg)	29	8
CO (kg)	11	30

Table 60: Wastewater Case Study Summary (treatment only)

Results	Centralized	Stonehurst	Corona
Energy (GJ)	17	57	52
GHG (Mg)	1	9	10
No_x (kg)	1	10	3
PM (kg)	0	6	7
SO_x (kg)	3	7	2
VOC (kg)	1	5	3
CO (kg)	11	26	9

12.2 Project Conclusions

The project conclusions are presented in two categories: Tools and Case Studies. General recommendations for research into the energy-water connection and the environmental impacts of water and wastewater systems are also discussed.

12.2.1 Tools

Conclusions related to WEST, WESTLite, and WWEST are listed below:

- WEST has been revised to allow significantly more customization since the Phase One version. Changes include allowing custom electricity mixes, customizing the water sources or process scenarios that can be analyzed, adding the sludge disposal activity, including EFs for additional air, water, and land emissions.
- WESTLite allows users to analyze small-scale design decisions related to piping and tank choices, possibly the most common design decisions in the water and wastewater industry.
- WWEST allows users to analyze wastewater systems using an LCA perspective. The tool was designed to be more user-friendly than WEST. WWEST contains many default assumptions so users do not need as much detailed data to get a basic assessment of their treatment process. However, results will be improved if data entry is complete, accurate, and detailed.

None of the tools assess all environmental emissions, account for ecological effects, or quantify environmental impacts such as human toxicity. For water systems, it does not address the sustainability of supply (ensuring that recharge is equal to or greater than withdrawal). Though the assessment of sustainability for water and wastewater system is not complete, it does fill a gap by allowing utilities to capture an element of environmental sustainability that has been previously ignored.

12.2.2 Case Studies

Conclusions related to the case study analyses are below:

- When small scale decisions about pipes and tanks are analyzed, steel pipe and tanks tend to be environmentally preferable over other materials (e.g., concrete and plastic).
- Custom electricity mixes, including renewable energy, can improve the environmental performance of water and wastewater systems. However, the impacts of renewable, or green, energy sources (e.g., solar, wind, geothermal) are not zero, as is often assumed, if one includes the life-cycle impacts of the manufacture and transport of equipment.
- Sludge disposal tends to have little impact on the results for water and wastewater utilities. However, the disposal choice is one of the few ways that utilities can create “negative emissions” (or emission savings) for GHG and other air pollutants. Selecting landfills that use gas to produce electricity or incinerators with energy or heat recovery can reduce the systems’ overall environmental impact, albeit marginally.
- Demand management, or conservation programs can provide an inexpensive and environmentally preferable alternative to water supply. Converting to low-flow toilets, in particular, can provide significant savings when implemented statewide. Four alternatives for conserving water outdoors are beneficial compared to water supply in this analysis: turf maintenance, xeriscaping, water pricing, and dormant turf.
- Desalination system can have a wide variety of impacts depending on the water source. In all cases, the energy use is higher than alternative water supply,given current technology.

- Wastewater system results can be significantly improved by using methane to offset other electricity supplies. For the case study utility herein, the plant is able to meet approximately 90 percent of its electricity needs using captured CH_4. The utility plant's GHG was 435 Mg per MG less than the potential emissions from the hypothetical plant.
- The economies of scale associated with centralized water and wastewater treatment plants results in lower energy requirements, for a given amount of treated water, relative to decentralized systems compared in this report.
- Case study results are site-specific and will vary by geography, hydrology, system design, water sources, and other factors. The case study results in this report can be used as guidance, but may not be directly applicable to other utilities.

12.3 Project Recommendations

The primary recommendation of this research is that WEST and WWEST should be introduced to utilities to educate them about the tools themselves and, perhaps more importantly, about life-cycle thinking itself. Utilities should be encouraged to take a long-term and life-cycle perspective on energy use and environmental emissions, including indirect emissions associated with the supply chain. LCA should be encouraged for design and planning of new water and wastewater systems and major system expansions and retrofits.

Other, more specific recommendations are summarized here:

- Desalination is an oft-discussed alternative for coastal water systems wanting a flexible and reliable water source. However, the energy and environmental effects should be accounted for in decision making. If implemented in several large cities, the impact on the state's energy supplies will be significant.
- Some wastewater treatment processes allow opportunities for heat and energy recovery which can offset fossil fuel consumption and prevent GHG emissions. Anaerobic treatment processes which produce CH_4 are particularly good candidates.
- Disposal choices may also be important for water and wastewater systems that want to limit environmental burden. Offsets with fuel or electricity consumption or generation as well as other materials (e.g., fertilizers) can be important to limiting the system's effect on the environment.
- California's climate change regulations are ground-breaking and encouraging for those concerned about long-term environmental health. However, this research shows that analyzing climate change effects requires a broader vision than the reporting required currently by the legislation.
- The interest in this research at the two workshops conducted as part of this work indicate that the researchers, and the Energy Commission, should keep the participants, and other interested parties, apprised of the latest research and tools available for evaluating these issues after this contract ends.

Water and wastewater design decisions are made based on several factors, including economic, engineering, and political concerns. The comprehensive and systemwide life-cycle environmental effects of the water infrastructure have not been a factor in these decisions. Generally, utilities, designers, and system 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, WWEST, or similar methodology should be conducted routinely. This would allow the industry to develop a comprehensive list of design recommendations for systems of differing parameters (e.g., scale, water quality, process selection). The model and tools 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.

GLOSSARY

Term	Definition
AC	Asbestos cement
AF	AF
AF	acre-foot
Assump	Assumption worksheet designation
AWWA	American Water Works Associate
Calc	Calculation worksheet designation
CBOD	Carbonaceous oxygen demand
CH_4	Methane
CI	Cast iron
CIEE	California Institute for Energy and Environment
CII	Commercial, Institutional, and Industrial sector
CO	Carbon monoxide
CO_2(e)	Carbon dioxide equivalents
COL	Collection
COM	Scenario: A commercial facility (i.e., big box store) in the desert region
Conv	Conversion worksheet designation
CRA	Colorado River Aqueduct
d	Day
DEF	Default calculation worksheet designation
DI	ductile iron
DIS	Distribution (water) or discharge (wastewater)
EBMUD	East Bay Municipal Utility District
EF	Emission factor
EGRID	Emissions and Generation Resource Integrated Database
EIO-LCA	Economic Input-Output Analysis-based LCA
Energy	California Energy Commission
EP	Energy production activity
EU	Equipment use activity
FEPA	Federal Energy Policy Act
g	gram
g/kWh	grams per kilowatt-hour
gal	Gallon
GHG	greenhouse gas
GJ	Gigajoules
gpd	Gallons per day
gpd	gallons per day
gpm	gallons per minute
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWE	Global warming effect
GWP	Global warming potential
HC	Hydrocarbons

hh	Household
in	Inch
IND	Scenario: A 40,000 m2 (10-acre) industrial site in the central region
ISO	International Organization of Standardization
kl or kl	Kiloliter
km	Kilometer
LCA	Life-cycle Assessment
lpf	Liters per flush
lpm	Liters per minute
LTRT	Liquid treatment (wastewater)
m2	Square meters
m3	Cubic meter
MBR	Membrane bioreactor
MD	Material delivery activity
MF	Scenario: A hypothetical multi-family unit in the coastal region
Mg	Million grams
MG	Million gallons
mg/l	milligrams per liter
MGD	Million gallons per day
MJ	Megajoules
Ml or Ml	Million liters
MMWD	Marin Municipal Water District
MP	Material production activity
MSW	Municipal solid waste
MWh	Megawatt-hours
N2O	Nitrous oxide
NA	Not available
NC-Current	Northern California case study utility (Current Water Supply)
NC-Proposed	Northern California case study utility (Proposed Water Supply)
NMVOCs	Non-methane volatile organic compounds
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
OWD	Oceanside Water District
PE	Polyethylene
PIER-EA	Public Interest Energy Research- Environmental Area
POE	Point of entry
PM	Particulate matter
PV	Photovoltaics
PVC	Polyvinyl chloride
PVDF	Polyvinylidene flouride
RO	Reverse osmosis
SC	Southern California case study utility
SD	Sludge disposal activity

SETAC	Society for Environmental Toxicology and Chemistry
SF1	Scenario: An average-sized single family home and lot in the coastal region
SF2	Scenario: An average single family home and lot in the inner coastal region
SF3	Scenario: An average sized single-family home and lot in the desert region
SF4	Scenario: A single family home on a large lot in the central region
SOx	Sulfur oxides
SPU	Seattle Public Utility
STRT	Sludge treatment (wastewater)
SWP	State Water Project
Tg	Teragrams
TJ	Terajoules
TRT	Treatment
TWD	Tampa Water Department
U.S. EPA	United States Environmental Protection Agency
UV	Ultraviolet
VOC	Volatile organic compounds
WEST	Water-Energy Sustainability Tool
WWEST	Wastewater-Energy Sustainability Tool
WWTP	wastewater treatment plant
yr	Year

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