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Life-cycle Energy Assessment of Alternative Water Supply Systems in California

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

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

Primary Author(s):
Arpad Horvath
Jennifer Stokes

University of California, Berkeley
Department of Civil and Environmental Engineering
215 McLaughlin Hall
Berkeley, CA 94720-1712
510-642-7300

Contract Number: CIEE Award No. MR-06-08

Prepared for:

California Energy Commission

XXXX XXXXXX
Contract Manager

Joe O'Hagan
Project Manager

XXXX XXXXXX
Office Manager
Name of Office Goes Here

XXXX XXXXXX
Deputy Director
Division Name Goes Here

Melissa Jones
Executive Director

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PREFACE

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

The PIER Program conducts public interest research, development,, and demonstration (RD&D) projects to benefit California.

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

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

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

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 (CIEE award no. MR-06-08) conducted by the University of California, Berkeley. The information from this project contributes to PIER's Water End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

Providing water and wastewater services in California is often energy-intensive. The need for alternative water sources (e.g., 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 (LCA) is a quantitative, comprehensive methodology 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, LCA was used to evaluate water and wastewater systems in California by 1) creating and revising decision-support tools, the Water-Energy Sustainability Tool (WEST) and Wastewater-Energy Sustainability Tool (WWEST), 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 (i.e., 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; and
- 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 energy significantly affects the environmental effects of water. Worldwide, pumping and treating urban water and wastewater consumes as much as three percent of energy which will only increase as population and demand for better treatment and sanitation increases. In California, water-related services use significant portions of the state's electricity use 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 a considerable energy and environmental cost.

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 effluent 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, 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 environmental burden. The energy and materials used and the construction processes needed to install this infrastructure 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 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 framework that allows a utility to more comprehensively compare the 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, 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. Accounting for energy and environmental effects in water planning requires life-cycle assessment, a systematic methodology to account for energy, materials, and other resource use and environmental outputs caused by extracting raw materials, transportation, and manufacturing, constructing, operating, and maintaining the water supply infrastructure.

Purpose

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 details of that project are reported in Commission Publication CEC-500-2005-101. The original project was 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 by making it more comprehensive, precise, and robust, as well as add case studies.

The 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. Using life-cycle assessessment methodology, two Microsoft Excel-based decision support tools were the primary deliverables of this project. The Water-Energy Sustainability Tool (WEST) was revised and the Wastewater-Energy Sustainability Tool (WWEST) was created to provide calculators of the energy and environmental implications of infrastructure associated with California's water and wastewater systems.

Objectives

The objectives, or tasks, for this project were as follows:

- Revise WEST to assess alternative energy sources and custom energy mixes, including options for renewable energy from solar, wind, and biomass sources.
- Update WEST to analyze other scenarios (i.e., groundwater, surface water, or alternative treatment processes) or alternative scenarios (chlorine vs. ultraviolet disinfection).
- Create a simplified tool which will calculate emission factors for common materials in water and wastewater systems such as pipe materials and tank design.
- Improve WEST to include the life-cycle effects of electricity generation so that the effects of mining, processing, and transporting fuel from its source to the point of combustion, and manufacturing and transporting all associated equipment are accounted for.
- Evaluate demand management measures and compare them to water supply alternatives.
- Revise WEST to consider additional air pollutants as well as water and land pollutants.
- Create a tool to analyze the energy demand of wastewater systems (WWEST).
- Develop workshops for industry professionals.
- Improve material production analysis of certain materials that are not well-defined in the existing tools, especially chemicals and plastics.
- Evaluate decentralized water and wastewater systems.

- Evaluate case studies to demonstrate the capabilities of WEST and WWEST.

Conclusions and Recommendations

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

- WEST has been revised to allow significantly more customization. Changes include allowing custom electricity mixes, 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.
- WWEST allows users to analyze wastewater systems using a life-cycle assessment perspective. The tool was designed to be more user-friendly than WEST. In particular, 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 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 (e.g., 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 (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 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. In the case of the case study utility, the plant 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

alternatives 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, the 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.
- The economies of scale associated with centralized water and wastewater treatment plants result in lower energy requirements for a given amount of treated water, relative to decentralized systems compared in this report.

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

- WEST and WWEST should be introduced to utilities to educate them about the tools themselves and, perhaps more importantly, about life-cycle thinking. 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 an oft-discussed alternative for coastal water systems wanting 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 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 or lower greenhouse gas emissions. Anaerobic treatment processes which produce methane are particularly good candidates.
- Disposal choices may also be important for water and wastewater systems that want to limit their environmental burden. Offsets of fuel or electricity consumption as well as other materials (e.g., fertilizers) can be important to limiting the system's effect on the environment.
- The interest in this project at the two workshops conducted as part of this work indicate that the researchers and the Energy Commission should try to keep the participants, and other interested parties, appraised 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 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 strive for sustainable solutions with more informed analyses.

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).

Problem Significance

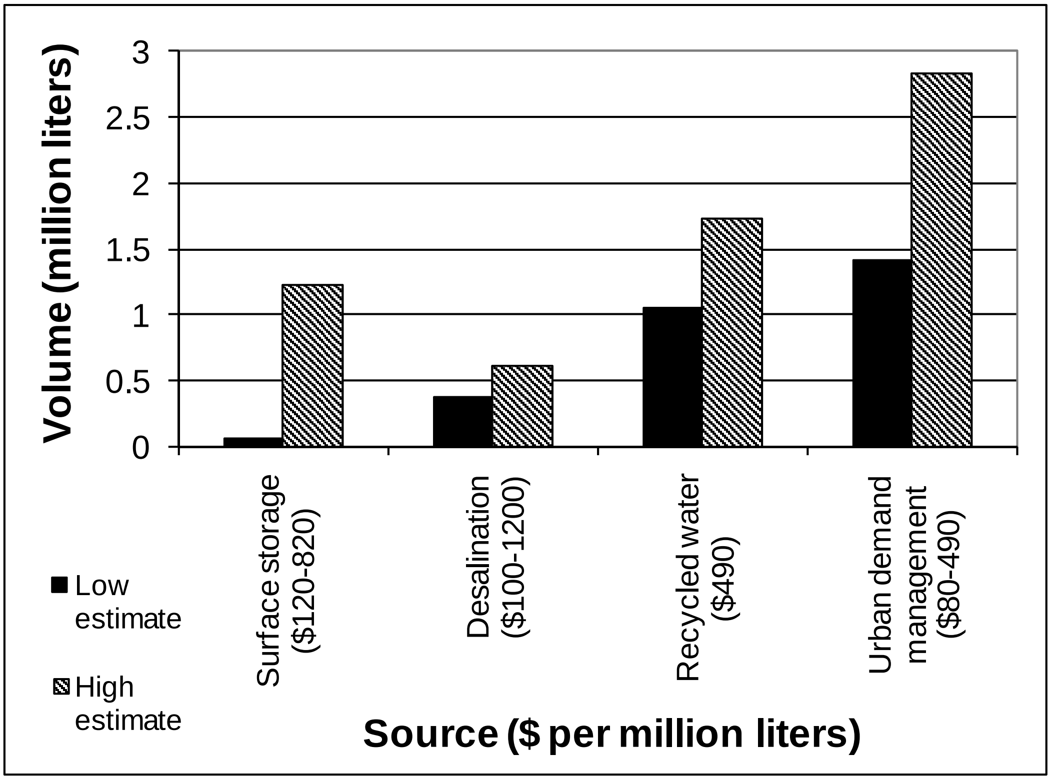
The scarcity of drinking water is a growing issue throughout many parts of the world, with 1.8 billion people located in areas likely to experience absolute water scarcity by 2025 (United Nations 2006). When relying solely on locally available freshwater, more than 40 percent of the world's population 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 1-1 depicts costs and potential volumes available for water sources in Southern California.

Figure 1-1: 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 occur 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.

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.

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.

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.2.3.

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)

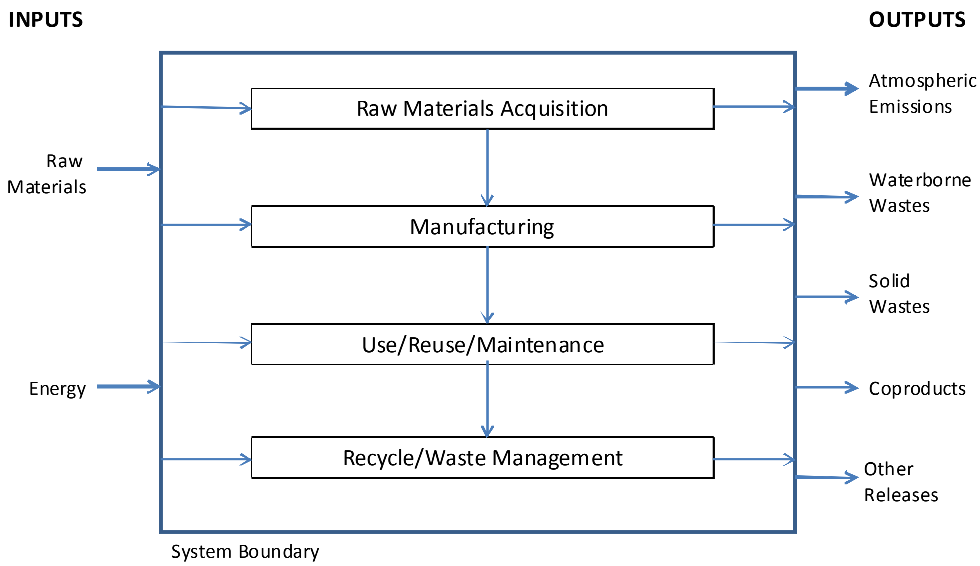
Literature Review

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 1-2 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 1-2: 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.

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 1-1 provides a summary of findings from other key water LCAs. Table 1-1 also includes distinctions between those studies and the one presented in this report. Only one of the studies listed in Table 1-1 evaluated infrastructure in the United States (Filion et al. 2004) and none of the studies explicitly used a hybrid LCA approach.

Table 1-1: 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 1-2 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 1-2: 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)

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).

Task 2 Approach

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.

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 2-1 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 2-1: 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

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 2-2 shows energy production and overall results.

Table 2-2: 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.

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.

Task 3 Approach

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.

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).

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 3-1 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.

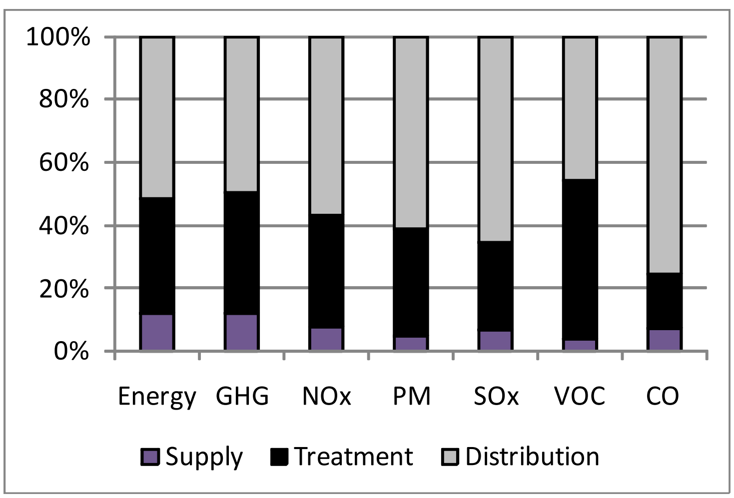
Table 3-1: Summary of Results for the Water Sources Comparison Study

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 1b, 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.

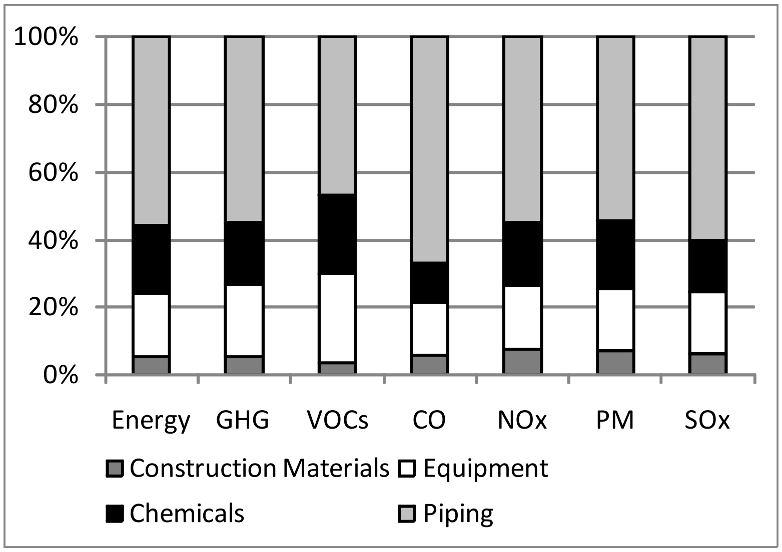
Figure 3-1 shows the breakdown of the results for the utility by water supply phase (supply, treatment, or distribution). The figure shows that for the water sources used by this utility, distribution dominates the results. For this utility, the distribution system is exceptionally expansive and energy-intensive. The service area's topography is very hilly and, as a result, the communities served by the utility are spread out.

Figure 3-1: Results by Water Supply Phase



In addition, Figure 3-2 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 3-2: 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 3-2 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 3-3.

Table 3-2: 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 3-3: 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's 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 3-4 and 3-5 provide results for the overall utility system using the revised electricity assumptions. Table 3-4 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 3.5.

Table 3-4: 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 3-5: 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 4.5 shows that desalination and local reservoir results are similar. However, the reservoirs provide almost three times more water to the overall system.

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.

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.

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 4-1 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 4-1: 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

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 5-2 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 4-2: 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

Task 4 Outcomes

The results for pipe and tank analyses are summarized below.

Pipe Analysis Outcomes

The outcomes of the pipe analysis are described in this section. A typical summary results page is shown in Figure 4-3. The results correspond to the input shown in Figure 4-1. Additional analysis assumptions are summarized in Appendix E.3.

Figure 4-3: 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 4-1; Table 4-2 shows the breakdown of components (i.e., pipe, gaskets, lining, coating) for two diameters of pipe (24 in. and 36 in.). Figure 4-4 shows the relative energy consumption of the considered scenarios.

Table 4-1: 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 4-2: 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 4-4: Energy Use Results for 100 feet of Pipe

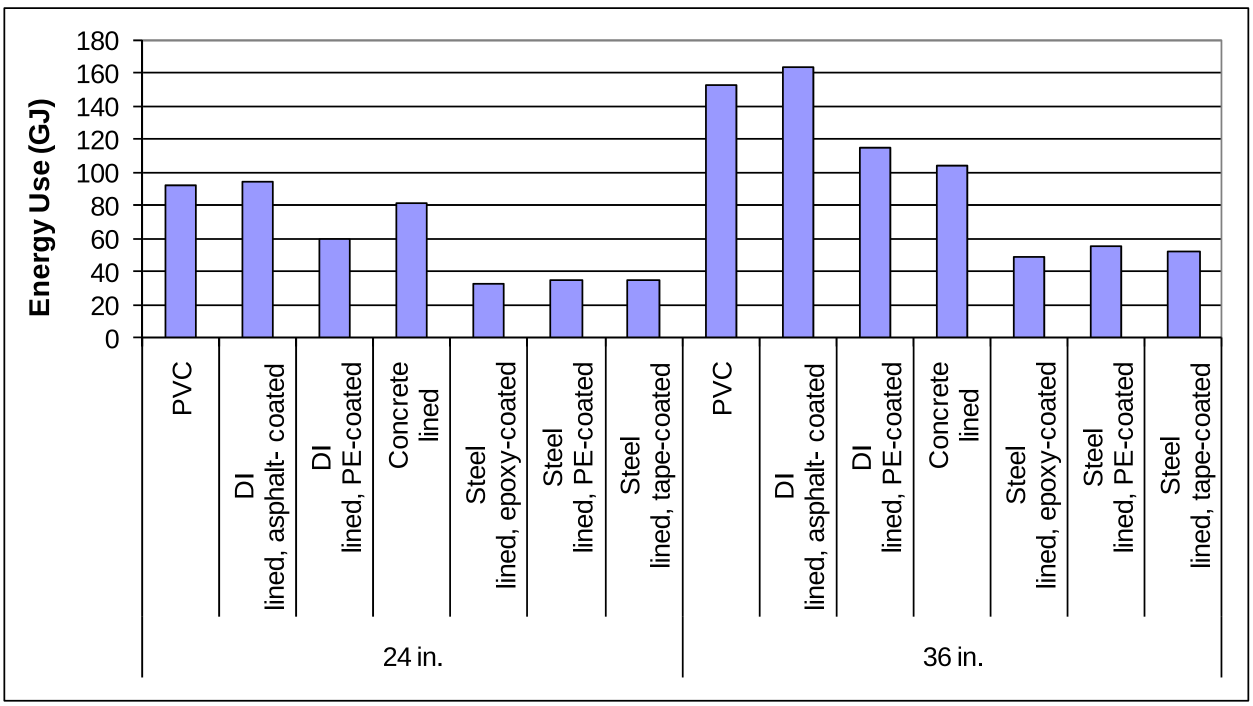


Table 4-2 shows that for all pipe types, except when asphalt coating is used, pipe manufacturing creates the majority of the effects. Asphalt coating is the most environmentally intensive; the coating itself produces 39 percent of the effects for the 24-inch pipe and 45 percent of the 36-inch pipe. This 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.

Tank Analysis Outcomes

Assumptions in the analysis are summarized in Appendix E.4. Figure 4-5 shows a typical summary results page. The results are for the input in Figure 4-2. 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 4-5: 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 4-3.

Table 4-3: 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 4-4. Results are reported in terajoules (TJ) for energy and Mg for air emissions. Table 4-5 provides results for the energy use contribution of each component to the final results. Figure 4-6 shows the results for constructing 10 MG of storage using each size tank (i.e., ten 1-MG tanks will be installed).

Table 4-4: 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 4-5: Tank Scenario Component Energy Results

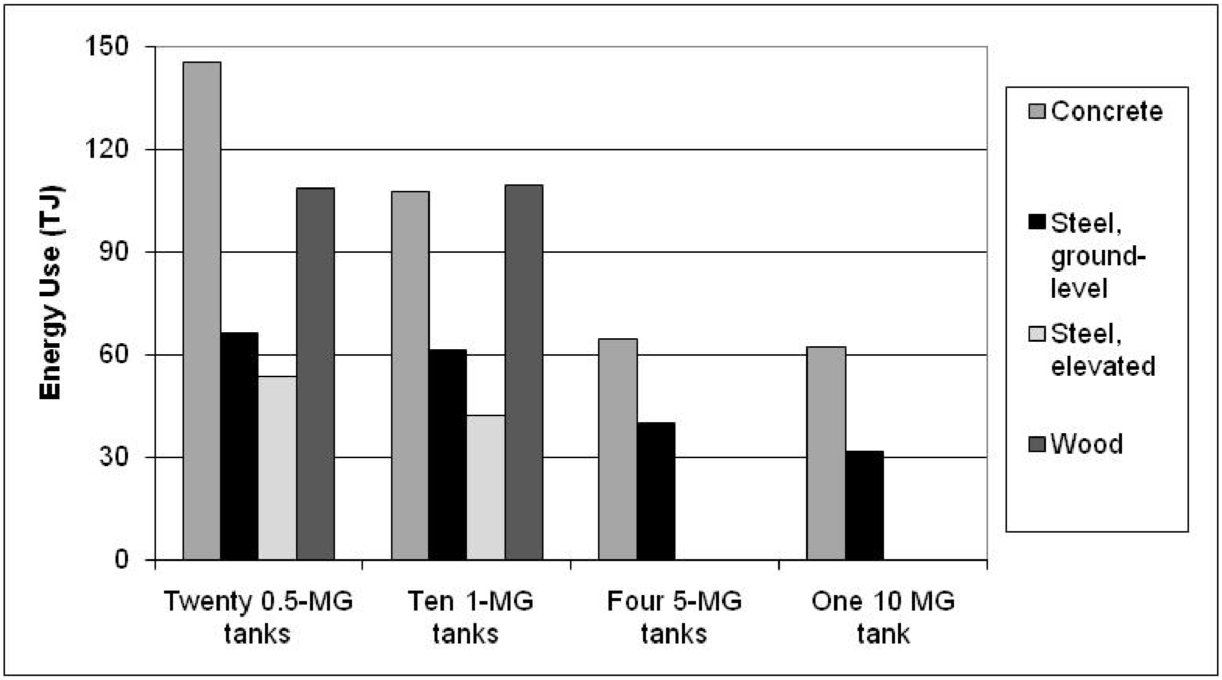
Material	Scenario One: 0.5 MG			Scenario Two: 1 MG			Scenario Three: 5 MG			Scenario Four: 10 MG		
	Tank	Found-ation	Energy or Pipe	Tank	Found-ation	Energy or Pipe	Tank	Found-ation	Energy or Pipe	Tank	Found-ation	Energy or Pipe
Concrete	67%	29%	4.1%	62%	32%	5.5%	54%	43%	2.3%	52%	47%	1.2%
Steel, ground-level	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 4-4 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 4-6 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 4-6: Results Summary for 10 MG of Storage



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.

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.

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 5-1, including both the revised direct and life-cycle values specific to California.

Table 5-1: 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 5-1.

The EF for each source was multiplied by its contribution to each state's resource mix. Figure 5-1 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 5-2) and international areas (Table 5-3) to use as guidelines for establishing custom EFs.

Figure 5-1: Energy Mix Data Entry Page

Electricity Mix Selection:

Scenario:	National Average Mix	
Default or User-defined Data:	WEST Default Values	Data in upper table will be used in calculations
Direct or Life-cycle Emission Factors:	Lifecycle Emissions	

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 5-2: Emission Factors 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 5-3: Emission Factors 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

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 5-4.

Table 5-4: 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
Landfill	No gas recovery		--	1.6	--	--	--	--	--
Landfill	Recovered gas flared	60%	--	0.44	--	--	--	--	--
Landfill	Recovered gas flared	75%	--	0.15	--	--	--	--	--
Landfill	Recovered gas flared	85%	--	-0.043	--	--	--	--	--
Landfill	Recovered gas flared	95%	--	-0.23	--	--	--	--	--
Landfill	Recovered gas for electricity	60%	--	0.25	--	--	--	--	--
Landfill	Recovered gas for electricity	75%	--	-0.08	--	--	--	--	--
Landfill	Recovered gas for electricity	85%	--	-0.3	--	--	--	--	--
Landfill	Recovered gas for electricity	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 5-4 are appropriate for general MSW.

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.

Task 5 Outcomes

Table 5-5 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 5-5: 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
	Desalinated	2500	5000	150	330	150	350	37	87	440	990	86	180	440	1000
	Recycled	1600	2100	93	130	81	120	21	31	270	360	48	68	270	360
	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
	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 5-2 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 5-2: Comparison of SC and NC Results

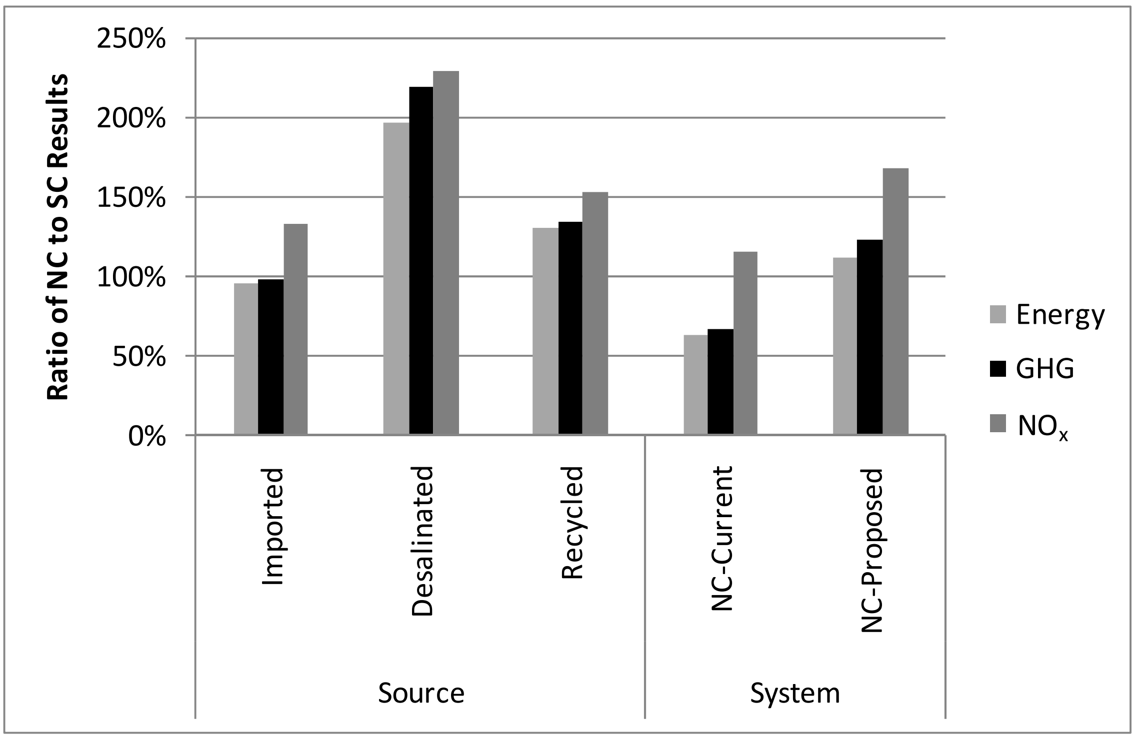


Figure 5-3 shows breakdown of results by activity for GHG and NO_x for each source from the case studies. GHG and NO_x were selected as generally representative of other emissions. Figure 5-3 shows that energy production is the most significant source of emissions for all sources, except NO_x from the 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 5-3: Activity Contribution to GHG and NO_x Results

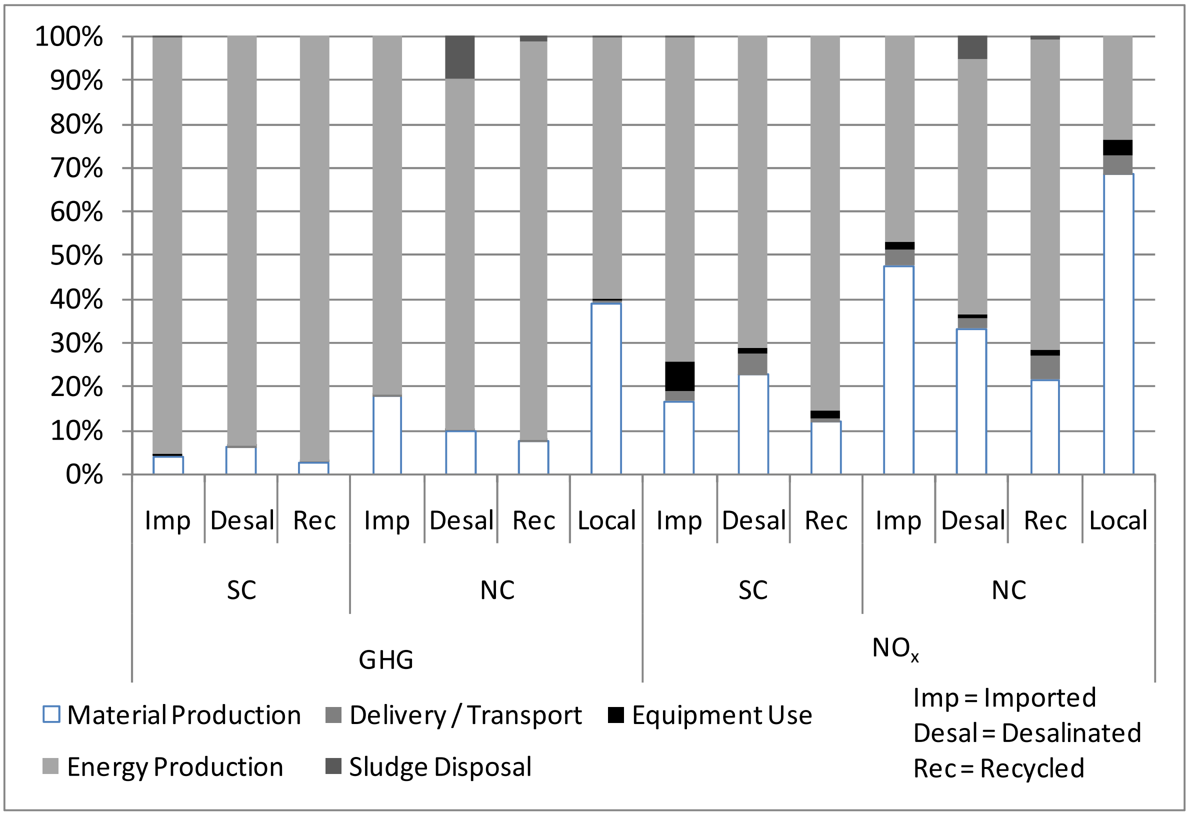


Figure 5-4 illustrates the contribution of life-cycle phases (construction, operation, maintenance, and end-of-life [EOL]). Figure 5-5 shows the contribution of water supply phases (supply, treatment, and distribution) to the overall system results (i.e., per 100 AF of water provided by the utility). 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 5-4: Life-cycle Phase Results for Utilities

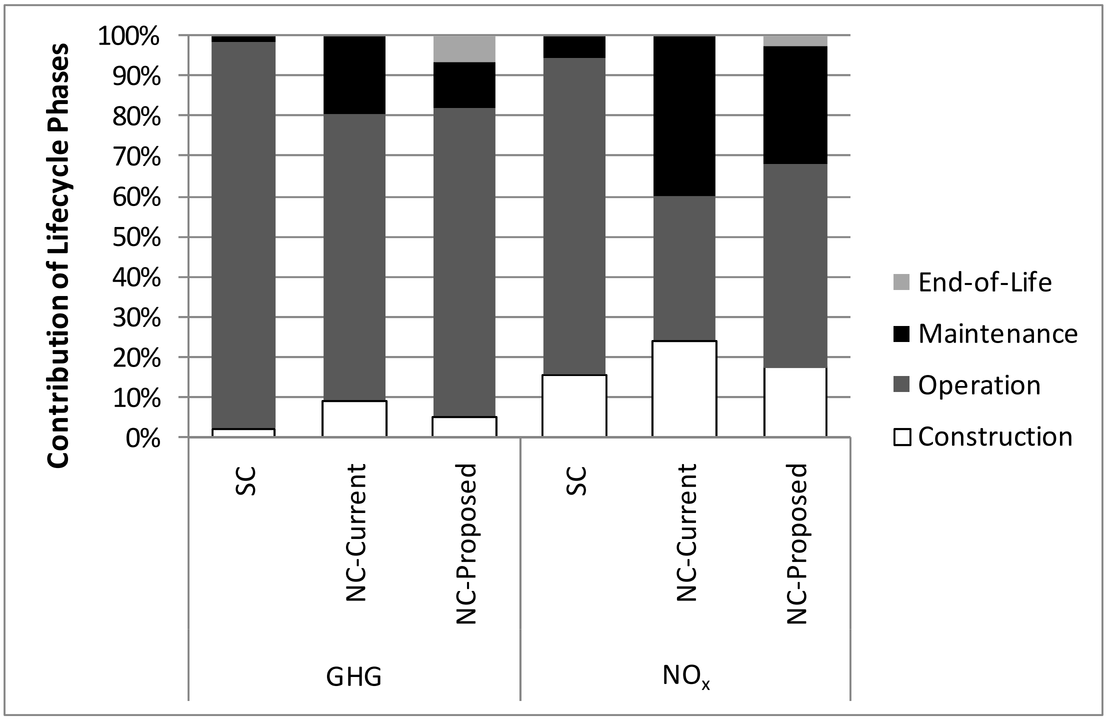
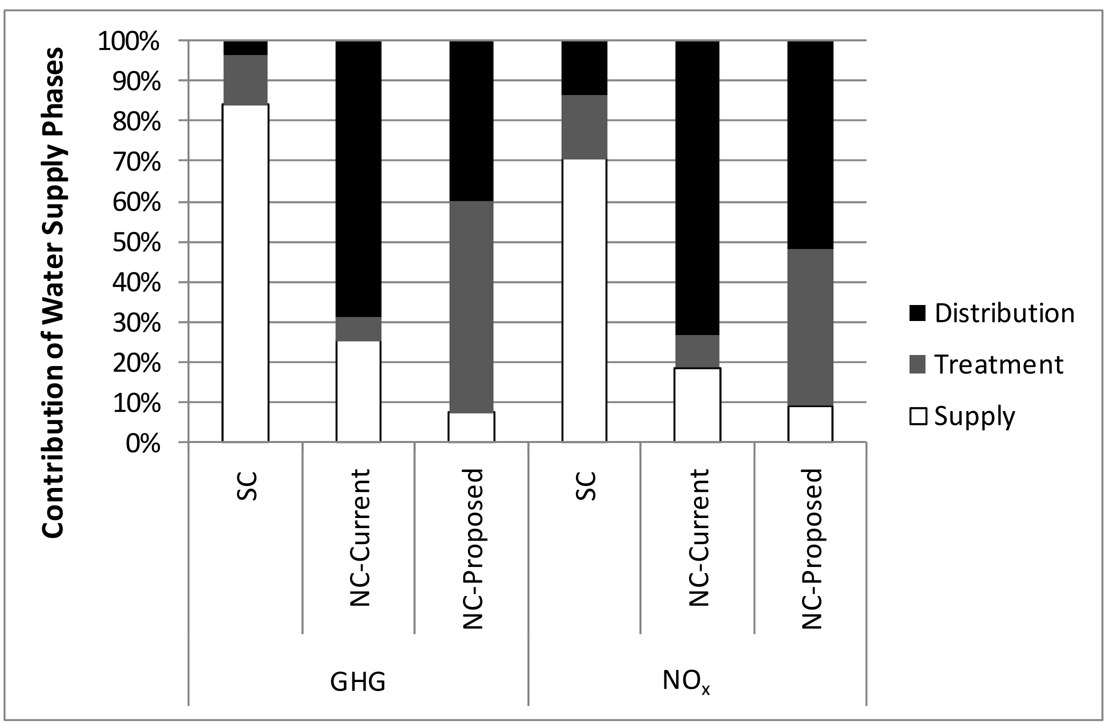


Figure 5-5: Water Supply Phase Results for Utilities



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.

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 6-1 summarizes the overall potential for water conservation according to the original report in units of million liters (Ml) per year.

Table 6-1: 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.

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 6-2 provides the relevant EIO-LCA EFs. Equations and summary calculations used in the analysis are described in Appendix F.1.

Table 6-2: 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 6-3 provides the ranges; median values were used for the calculations. Equations and sample calculations are shown in Appendix F.1.

Table 6-3: 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 6-2). 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.

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 6-1). 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 6-4. 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 6-4: 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 6-5.

Table 6-5: 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 6-5 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.

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 6-6 summarizes the relevant data for all toilet models.

Table 6-6: 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.

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 6-7.

Table 6-7: 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.

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 6-8 includes the relevant information for analyzing the faucet systems.

Table 6-8: 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.

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 6-9 includes the assumptions associated with washing machines included in this analysis.

Table 6-9: 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 6-2.

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.

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 6-10 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 6-10: Office Building Fixture Details

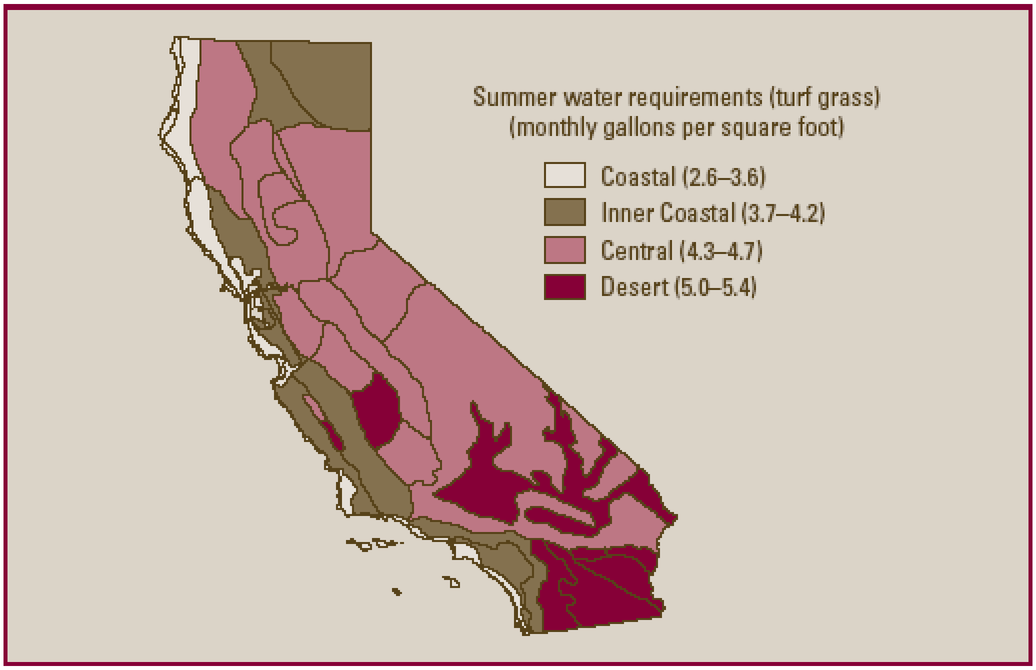
	Toilets		Urinals	
	Toilet 1	Toilet 2	Urinal 1	Urinal 2
Water Use (lpf)	61	3.8	3.8	0
Fixture price	$165	$440	$250	$450
Chemical ($/yr)	--	--	--	$25
Water savings (kl/yr)	65	85	34	102

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 6-1).

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 6-2. 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 6-1 provides ranges for estimates of E0 for each region.

Figure 6-1: 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 6-11. 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 6-11: 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

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).

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.

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.

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.

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").

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/m² for turf and $22/m² 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).

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.

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.

Task 6 Outcomes

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

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 6-12 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 6-3. Table 6-13 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 6-12: 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 6-13: 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 6-14.

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 6-14 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 6-14: Economic Impacts of Water Conservation

Lifecycle Costs ($) per kl/day Conserved/ Supplied		TOILETS				SHOWERHEADS				FAUCET: Aerators		FAUCET: Hands-free		WASHING MACHINES					
		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.

Indoor CII Demand Management Results

Table 6-15 summarizes both the material production environmental effects and the total economic costs associated with this scenario.

Table 6-15: 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.

Outdoor demand management results

Table 6-16 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 6-12. 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 6-16: 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 6-17 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 6-16 and 6-17 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 6-17 shows the water savings for certain alternatives, including water pricing and dormant turf.

Table 6-17: 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 6-18 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 6-18: 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

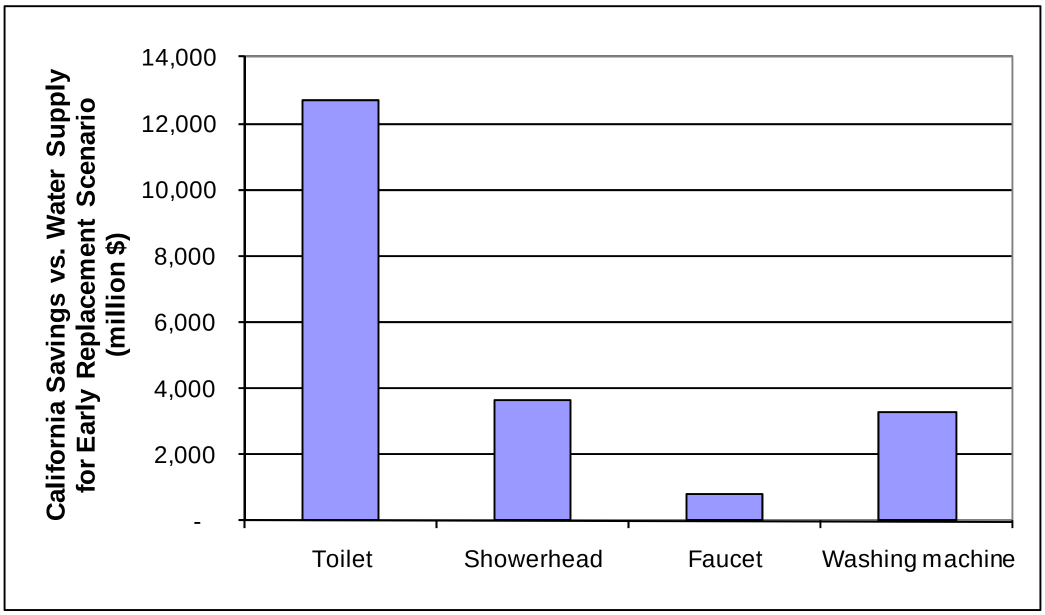
However, it should be noted that the results are sensitive to a number of factors, including yard size, irrigated area, turf area, plant types, topography (i.e., some scenarios could require pumping which was not included in the analysis), building size, material and water costs, etc. These results should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

Task 6 Conclusions and Recommendations

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 6-2 shows the statewide potential economic savings (including external costs) for the early replacement scenario.

Figure 6-2: 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 6-4) 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.

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 6-10 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.

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.

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.

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. Table 7-1 and 7-2 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 7-1: 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 7-2: 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

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 7-3. 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 7-3: 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 7-4.

Table 7-4: 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)

Task 7 Outcomes

The revisions to WEST were tested by analyzing a hypothetical scenario for providing desalinated water to Coastal California. Table 7-5 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.

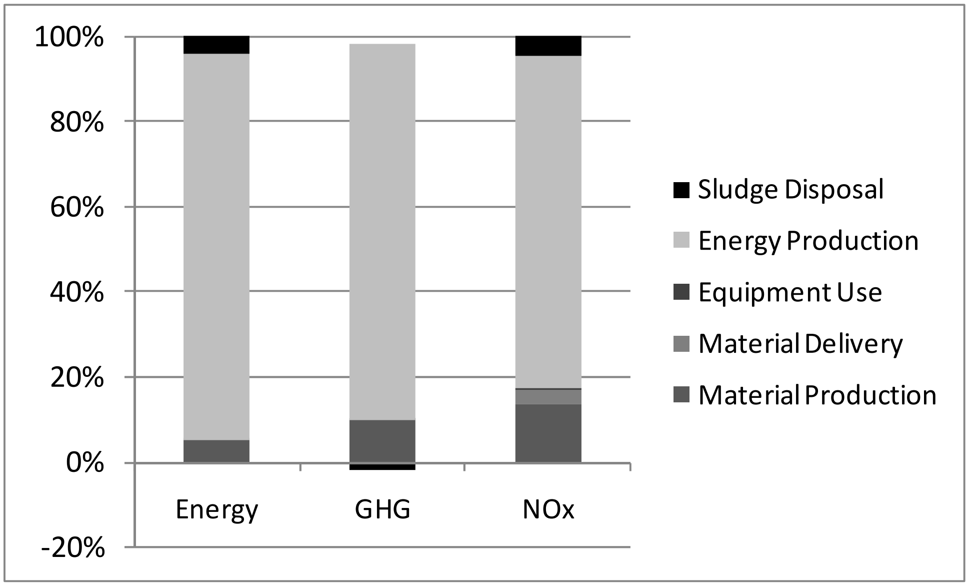
Table 7-5: Desalination Energy and Air Emission Results

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 7-1 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 7-1: Desalination Results by Activity



Tables 7-6 and 7-7 list the expanded emissions added as part of Task 7. Table 7-6 shows land and air emissions. Table 7-7 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 7-6: 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 7-7: 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.

Task 7 Conclusions and Recommendations

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.

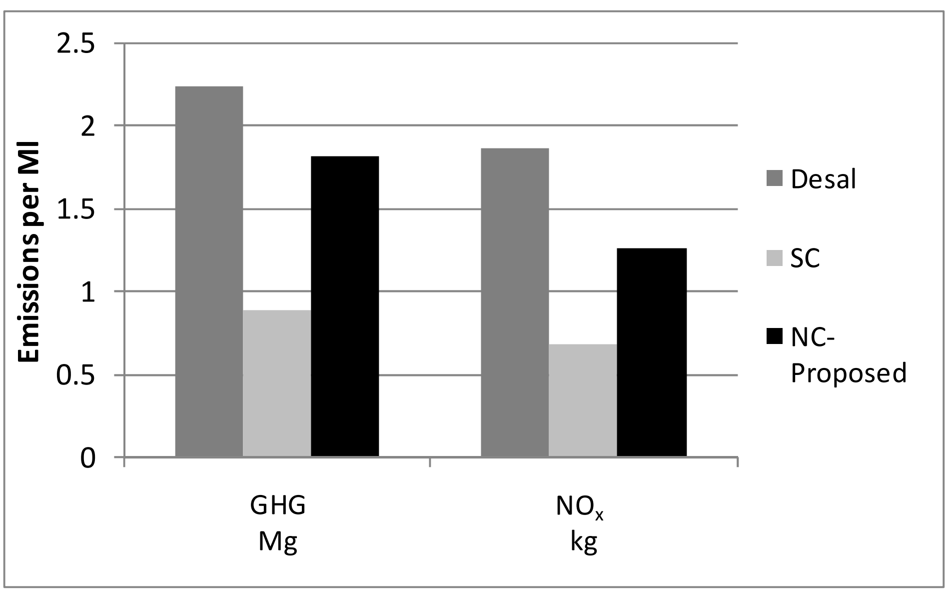
A potential future improvement to the tool would be to place these results into a more meaningful context. For instance, they could be normalized by their expected toxicity or effect on water quality. Instead of seeing a chemical-by-chemical list, the results would be contextualized to a more meaningful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

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 7-2 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 7-2: 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.

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.

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.

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.

Task 9 Approach

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).

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.

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 9-1 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 9-1: 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.

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 9-2 provides case study details. Sludge disposal information was not provided by the utility and was not included in the analysis.

Table 9-2: 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.

Task 9 Outcomes

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.

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).

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 9-3.

Table 9-3: NC-Large Results Summary for Sources and System

Constituent	Source			Overall
per M	Imported	Reservoir	Stored	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 9-1 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 9-1: NC-Large System Energy Results by Life-cycle Phase

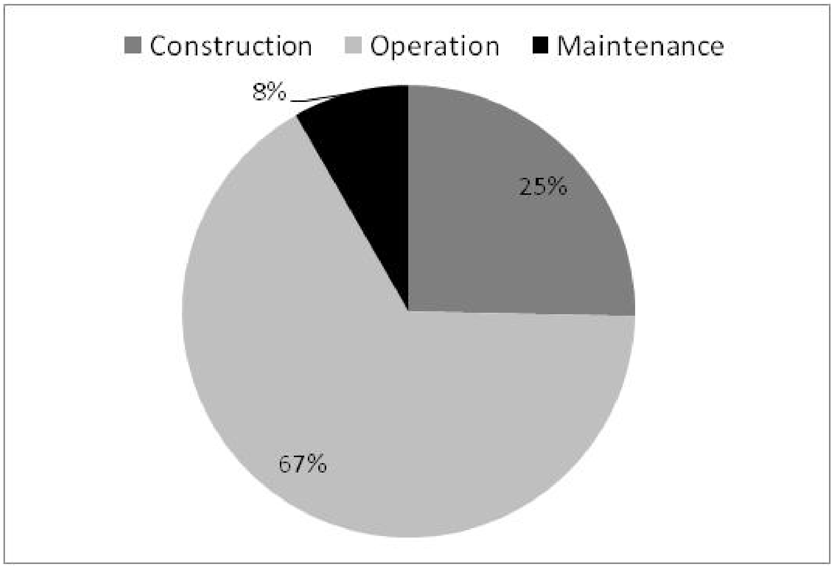
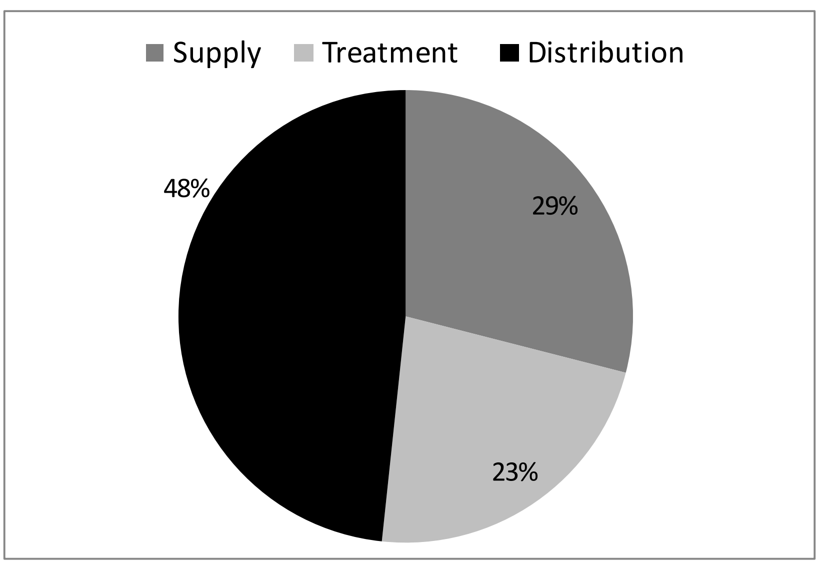


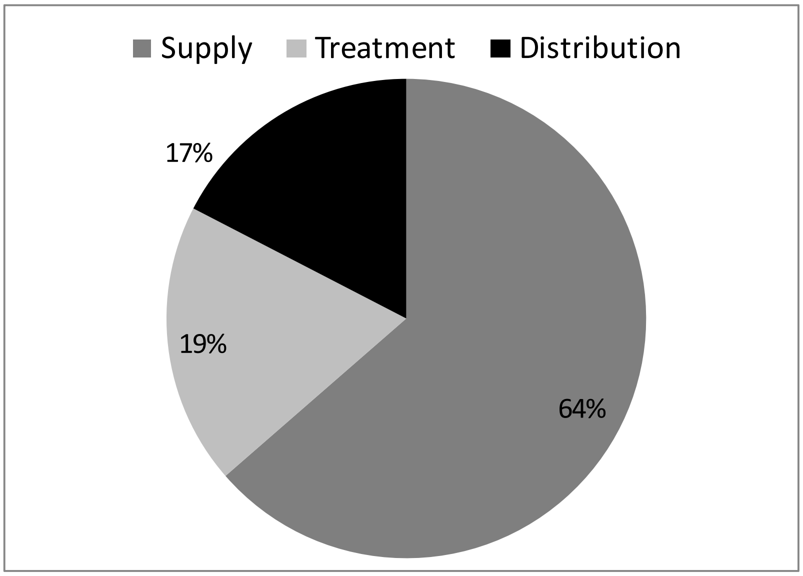
Figure 9-2 summarizes the system energy results by water supply phase. The supply phase (29 percent) consists of aqueducts, reservoirs, and pump stations. The treatment phase (23 percent) includes all activities at the treatment plants, including filter replacement and chemical consumption. The distribution phase (48 percent) is composed of pipes, pumps stations, tanks, and valves needed to move treated water to customers in the service area.

Figure 9-2: NC-Large System Energy Results by Water Supply Phase



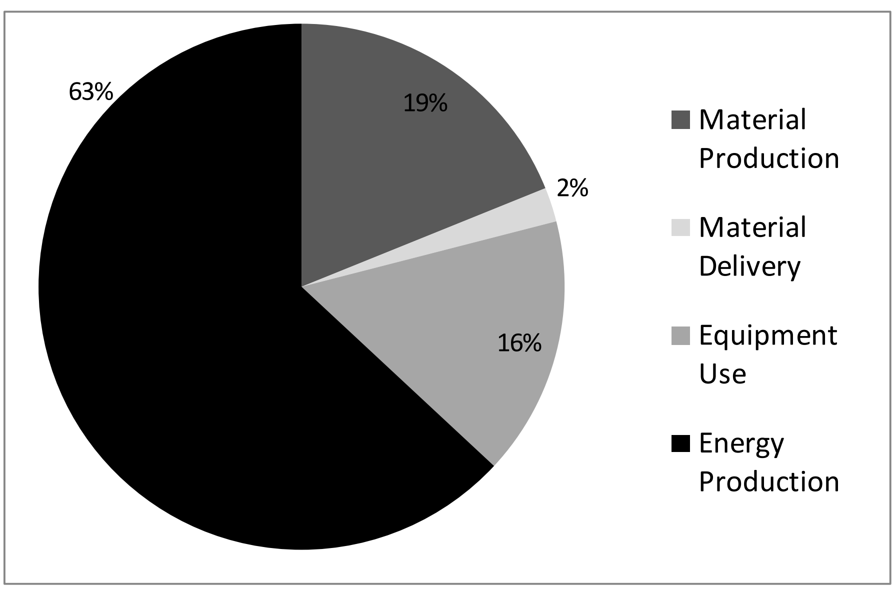
The system results consist primarily of imported water. Figure 9-3 shows the same breakdown for the local reservoir component of the water supply. In this case, the supply phase comprises about two-thirds of the results.

Figure 9-3: 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 9-4 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 9-4: NC-Large System Energy Results by Activity



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 9-4.

Table 9-4: NC-Small Results Summary for Sources and System

Constituent per million liters	Source: Treated Groundwater	Source: 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 9-5 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 9-5: NC-Small System Energy Results by Life-cycle Phase

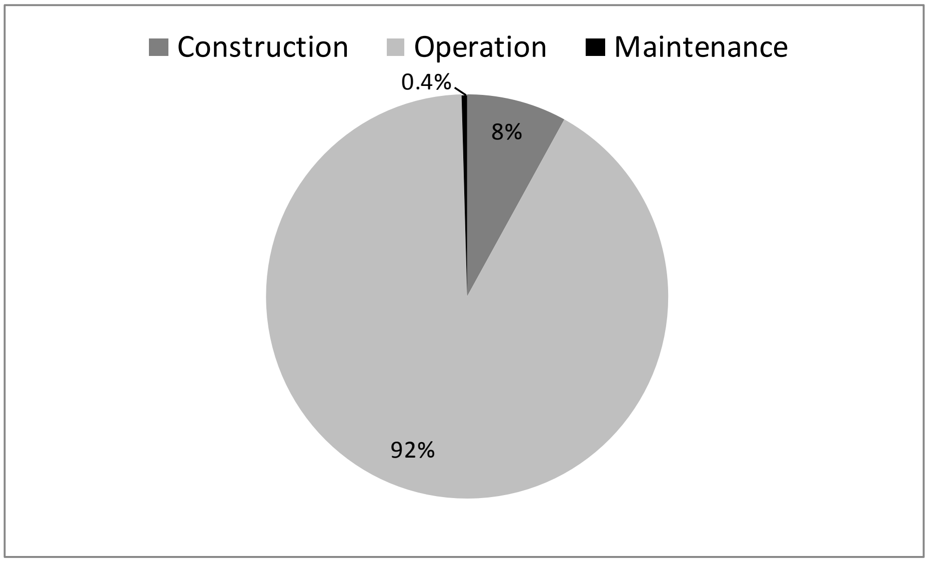


Figure 9-6 summarizes the NC-Small energy results by water supply phase. The supply phase (33 percent) consists of groundwater wells. The treatment phase (20 percent) includes activities at the treatment plants, including chemical consumption. The distribution phase (47 percent) is composed of pipes, 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 9-6: NC-Small System Energy Results by Water Supply Phase

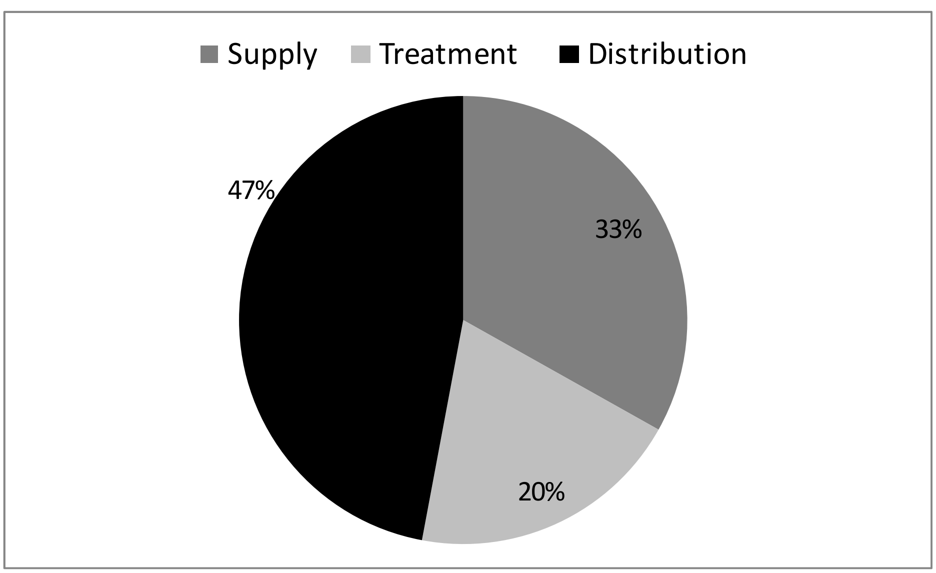
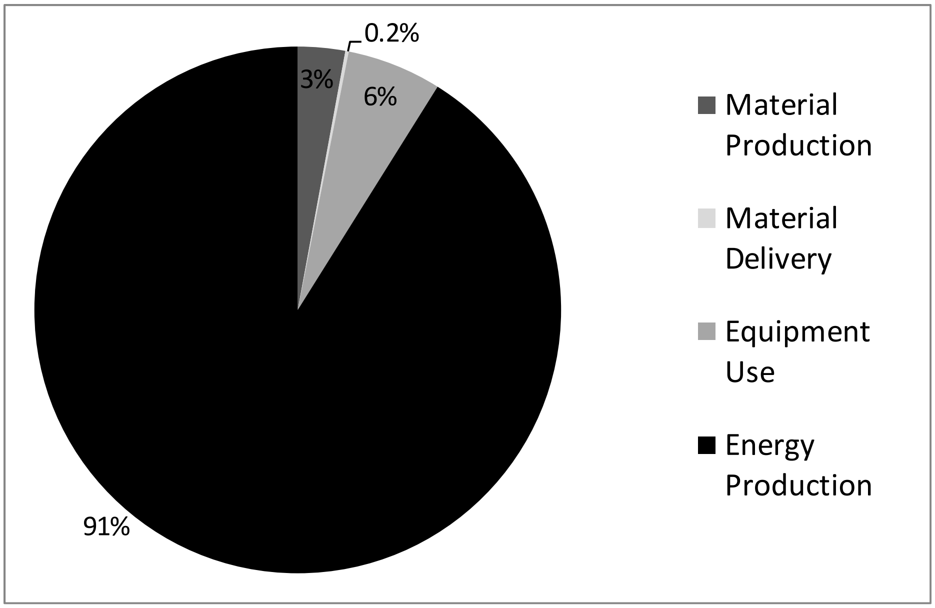


Figure 9-7 shows NC-Small's energy results broken out by activity. The most significant activity is energy production (92 percent). The small scale system and simple treatment process results in low material production results relative to prior case studies (2 percent).

Figure 9-7: NC-Small System Energy Results by Activity



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).

Task 10 Approach

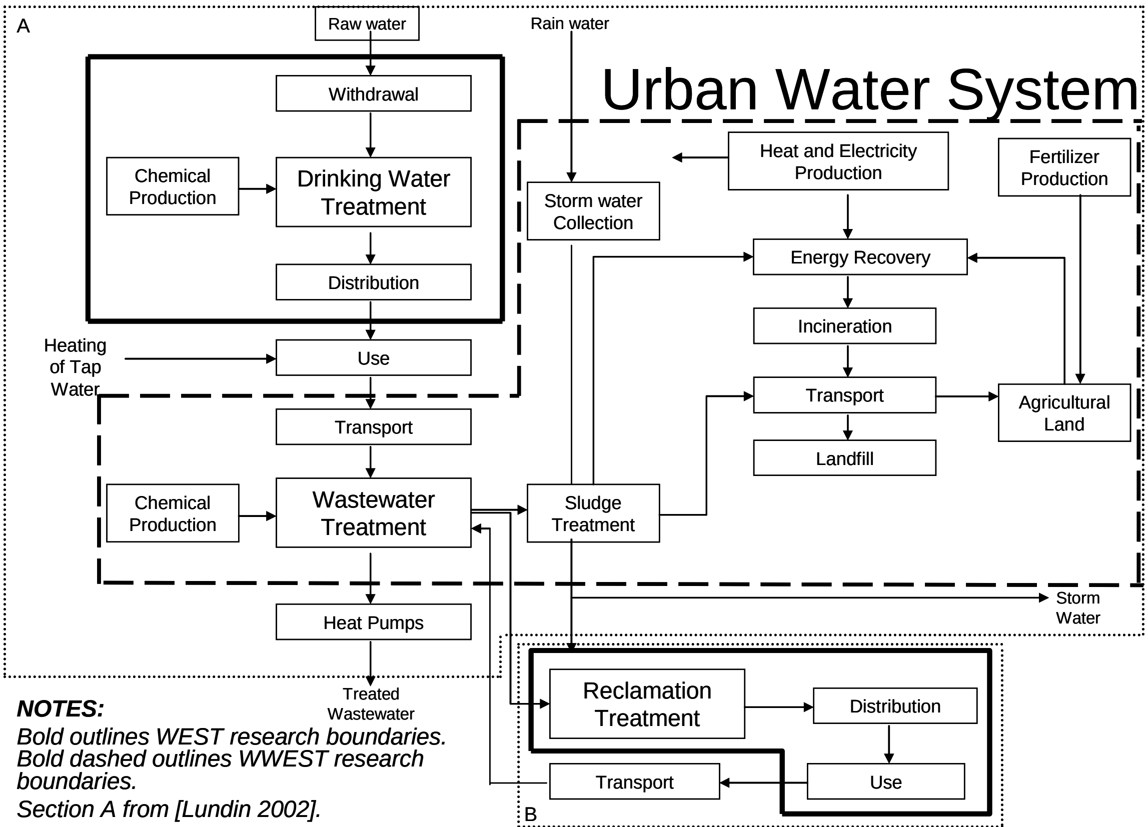
The framework of this study was to conduct an LCA of a large wastewater utility. LCA has been previously described in Chapter 1. Similarly to WEST, WWEST incorporates a form of hybrid LCA which leverages the strengths of each approach while minimizing the disadvantages. EIO-LCA was used to estimate emissions 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).

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 10-1 shows the boundaries which define the analysis in this study as well as the components included in the Phase One work.

Figure 10-1: Research Boundaries



NOTES:
Bold outlines WEST research boundaries.
Bold dashed outlines WWEST research boundaries.
Section A from [Lundin 2002].
Section B from [Stokes 2004]

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 10-1 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 10-1: 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.

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.

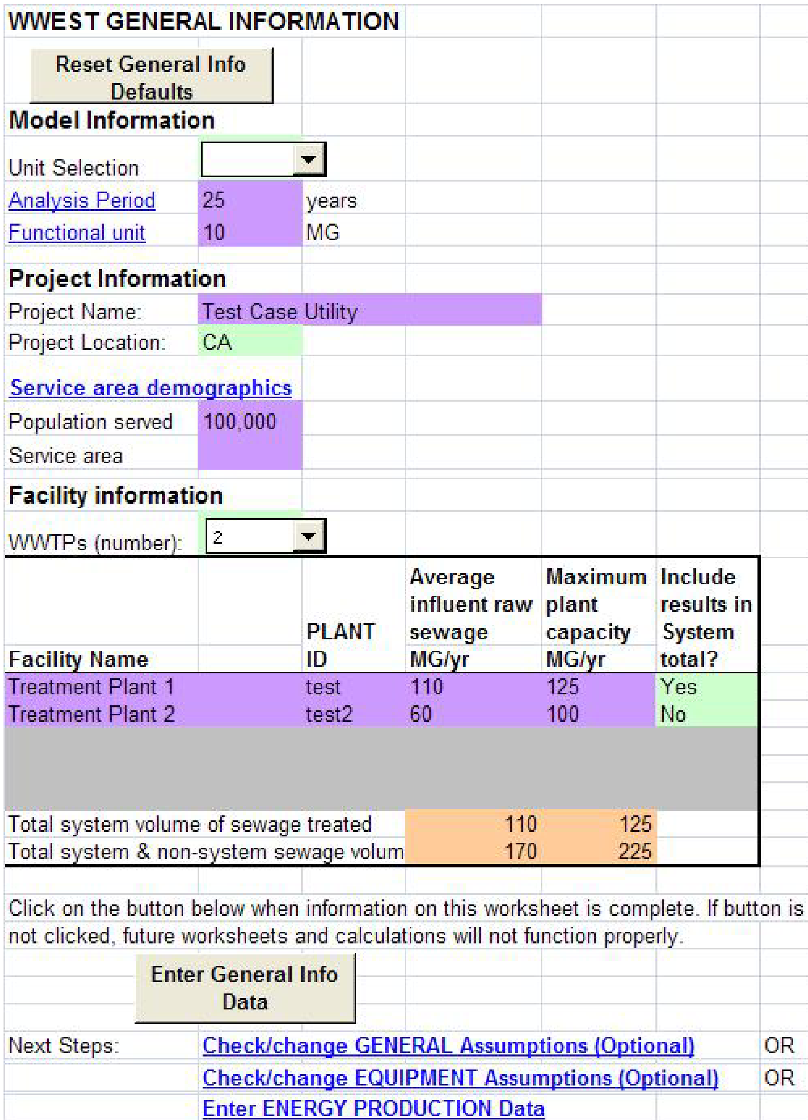
A general information page (Entry-General worksheet) requires the user to define model assumptions (units, analysis period, and functional unit), the name, location, and demographics of the system, and WWTP characteristics. Up to five WWTPs can be defined. Figure 10-2 shows the general data entry worksheet.

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 10-2: 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.

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 10-2 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 10-2: 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.

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 10-3 presents a sample results page for data to show how tabular results are presented . Figure 10-4 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 10-3: WWEST Sample Results Data Worksheet

TABLE 1: Summary Results

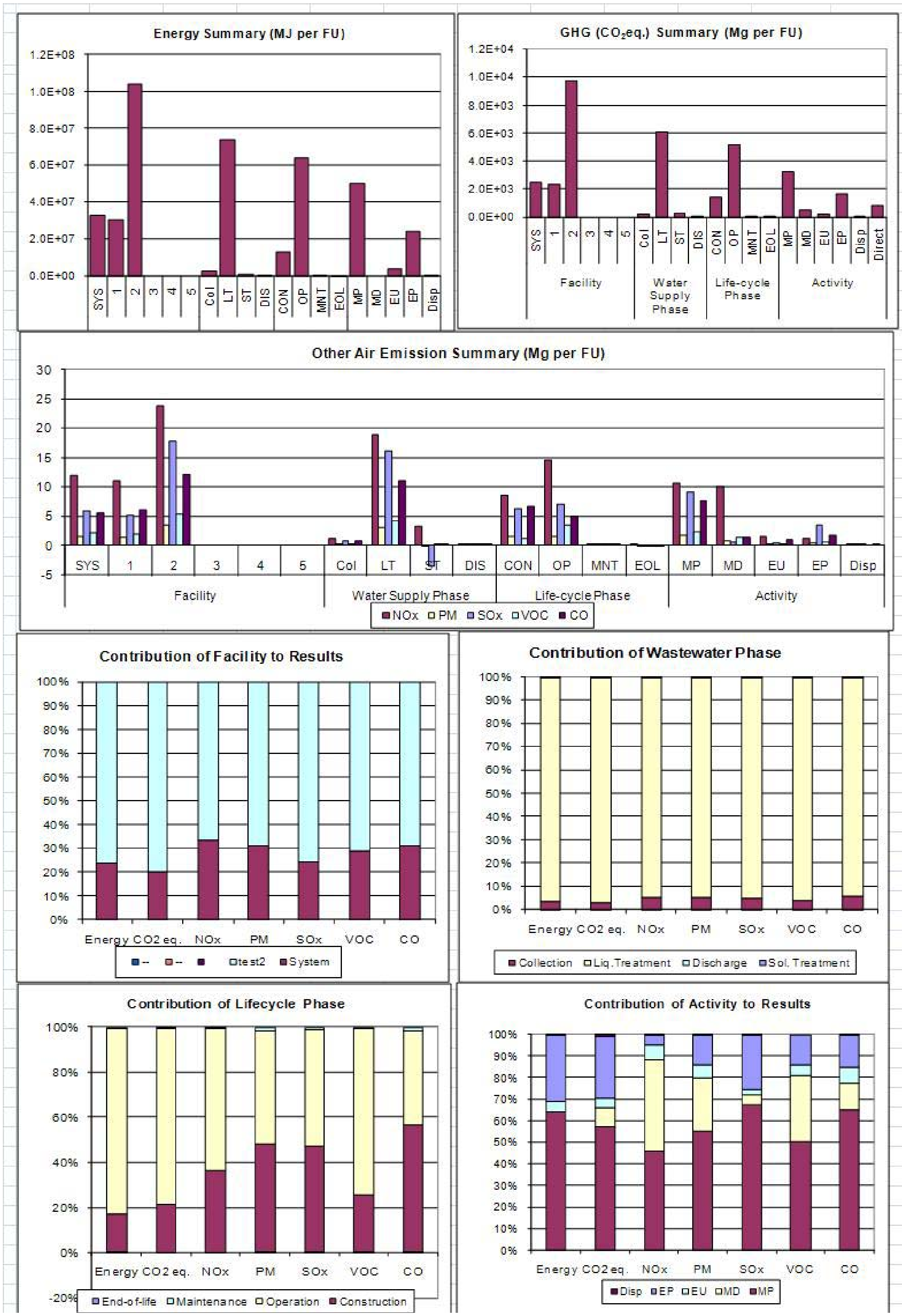
Chem-ical	Total	Weighted Total	Facility						Water Supply Phase				Life-cycle Phase				Activity					
			SYS	1	2	3	4	5	Col	LT	ST	DIS	CON	OP	MNT	EOL	MP	MD	EU	EP	Disp	Direct
Results per functional unit (MJ for energy, Mg for other)									Functional unit =			1.0E+01	MGD									
Energy	2E+08	8E+07	3E+07	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 10-4: WWEST Sample Results Graphs Worksheet



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.

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.

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 10-3 summarizes the volume of liquid and sludge processed in the system.

Table 10-3: 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.

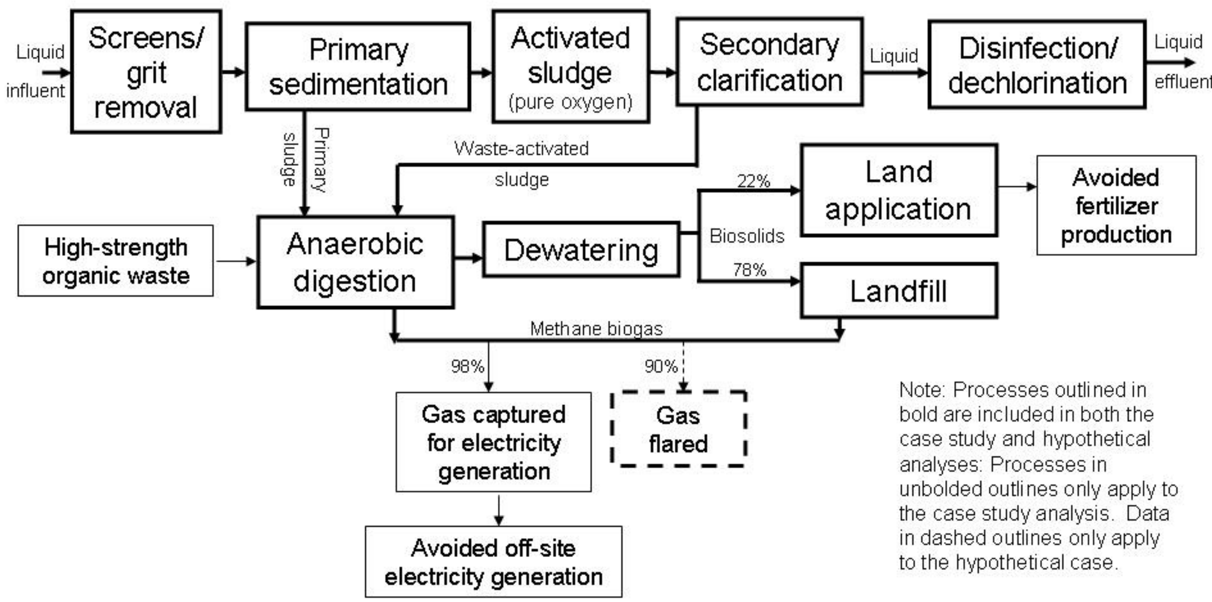
Collection Infrastructure Summary

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.

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 10-5 shows a process diagram of the treatment process. Chemical consumption for liquid and sludge treatment are summarized in Table 10-4.

Figure 10-5: WWTP Process Diagram



Source: Stokes and Horvath 2011

Table 10-4: 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

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.

Energy Consumption and Recovery Summary

Energy is consumed by the utility as electricity, natural gas, and diesel fuel. Table 10-5 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. Energy recovery produced an average of 40,000 MWh annually over years 2005-2007.

Table 10-5: 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.			

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 10-6 summarizes the average annual miles traveled and gas mileage for each category of vehicle.

Table 10-6: 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

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.

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 10-7. The results for the case study utility and the hypothetical system are discussed in the sections below. The results are also discussed in more detail in (Stokes and Horvath 2010), a link for which can be found in Appendix B.1.

Case Study Results

As expected, the treatment phase dominates the results for both the utility and hypothetical system. The treatment phase contributes 88 percent of the energy consumption and 63 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. GHG and PM emissions are negative for the operation phase and drive the results significantly lower. For the utility’s other emissions, the operation phase is most important for energy use (76 percent); construction is more significant for NO_x (54 percent), SO_x (79 percent), and VOC (60 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 4 percent) to overall results.

Table 10-7: Wastewater Utility Energy Use and Air Emission Results

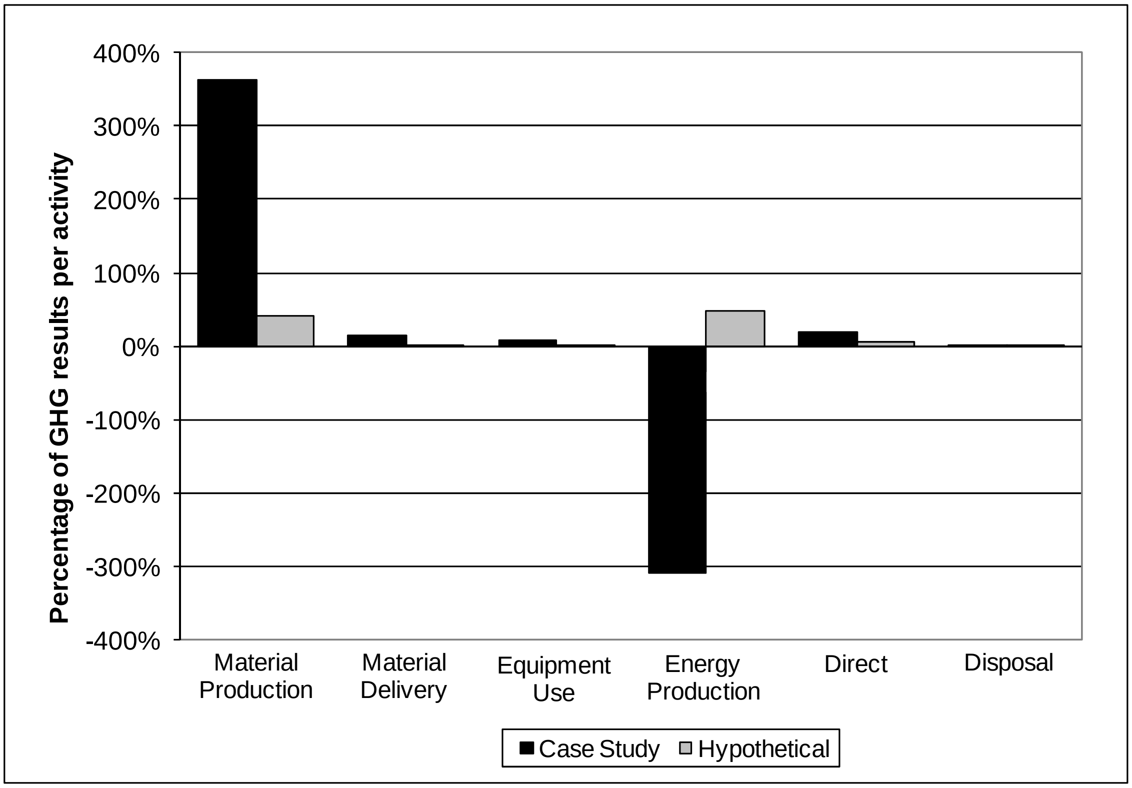
Results per ML (GJ energy, kg GHG, else g)	Energy	GHG	NO_x	PM	SO_x	VOC
Case Study						
Total	2.3	55	840	-290	470	100
Wastewater Phase Results						
Collection	0.26	20	100	17	79	17
Treatment	2.0	35	740	-310	390	80
Discharge	0.011	0.79	4.1	0.77	4.1	0.85
Life-cycle Phase Results						
Construction	0.52	71	450	87	370	60
Operation	1.7	-18	380	-380	92	36
Maintenance	0.032	2.3	12	3.3	9.3	2.7
End-Of-Life	-0.0049	0.56	2.2	-0.73	-0.020	-0.23
Activity Results						
Material Production	2.9	200	660	110	560	140
Material Delivery	<0.001	8.5	160	12	9.3	22
Equipment Use	0.1	4.8	20	4.7	4.5	4.0
Energy Production	-0.76	-170	-0.30	-410	-100	-67
Direct	--	11	--	--	--	--
Disposal	0.0030	1.1	2.5	0.55	0.35	<0.001
Hypothetical Results						
Total	6.4	490	1000	170	1100	260
Wastewater Phase Results						
Collection	0.26	20	100	17	79	17
Treatment	6.1	470	900	157	1000	240
Discharge	0.011	0.79	4.1	0.77	4.1	0.85
Life-cycle Phase Results						
Construction	0.52	71	450	87	370	60
Operation	5.9	410	530	84	720	200
Maintenance	0.032	2.3	12	3.3	9.3	2.7
End-Of-Life	0.0030	7.5	2.5	0.55	0.35	0.0060
Activity Results[1]						
Energy Production	3.4	240	150	50	520	97
Direct	--	34	--	--	--	--
Disposal	0.0030	7.5	2.5	0.55	0.35	<0.001

Note: Numbers may not sum due to rounding.

Source: Stokes and Horvath 2011

The case study results indicate that material production is a bigger contributor than energy production for the utility for all environmental effects. In fact, all emissions for energy production are negative due to the electricity offsets. This was not true for any of the water systems analyzed in prior phases of work and was unanticipated. In those cases, energy production dominated material production consistently. Figure 10-6 illustrates the GHG activity results for both the case study and the hypothetical system.

Figure 10-6: Greenhouse Gas Emissions by Activity



Source: Stokes and Horvath 2010

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 20 percent to the overall GHG results, or 11 kg per MG. 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 CH4 combustion.

Material delivery contributes appreciably to the emissions of GHGs, NO_x, and VOCs (15 percent, 19 percent, and 22 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 10 percent to all environmental effects. Disposal contributes 2 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 -117 Mg per MGD, compared with -160 Mg per MG 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 55 Mg.

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 (CH_4 not captured) 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 CO. Construction phase contributes 51 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, 46 percent of the consumption is from material production and 53 percent from energy production. Material and energy production comprise 41 percent and 40 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, 34 Mg of CO_2(e) per MG compared with 11 Mg for the utility. Direct GHG emissions are subsequently comparable to material and energy production (33 percent).

Material delivery contributes appreciably to the NO_x emissions (16 percent). For other air emissions, the effects are less than 10 percent of the overall results. The results are explained by chemical delivery, as described in the Utility results section. Equipment use contributes less than 3 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 230 Mg per MG, compared with 270 Mg 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

490 Mg. For this utility, the reported value would only capture less than half of the overall GHGs associated with the wastewater processing.

Task 10 Conclusions and Recommendations

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

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.

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 435 Mg per MG 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 6.4 Mg of GHG per MG.

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.

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.

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).

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.

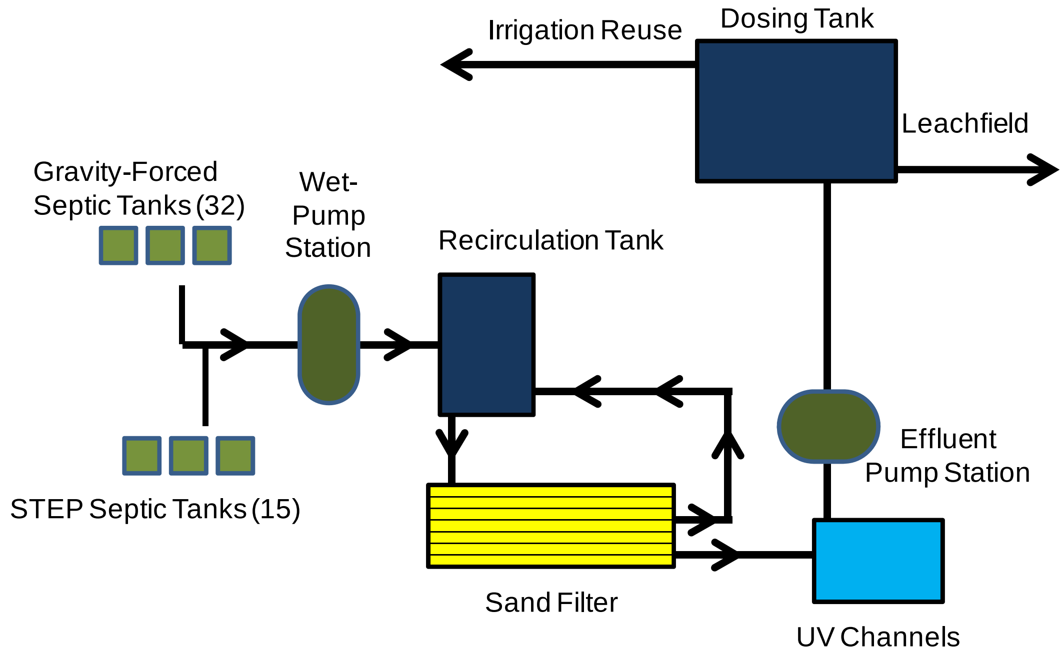
Case Studies

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.

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 11-1 presents a schematic of the decentralized wastewater treatment system in the Stonehurst development.

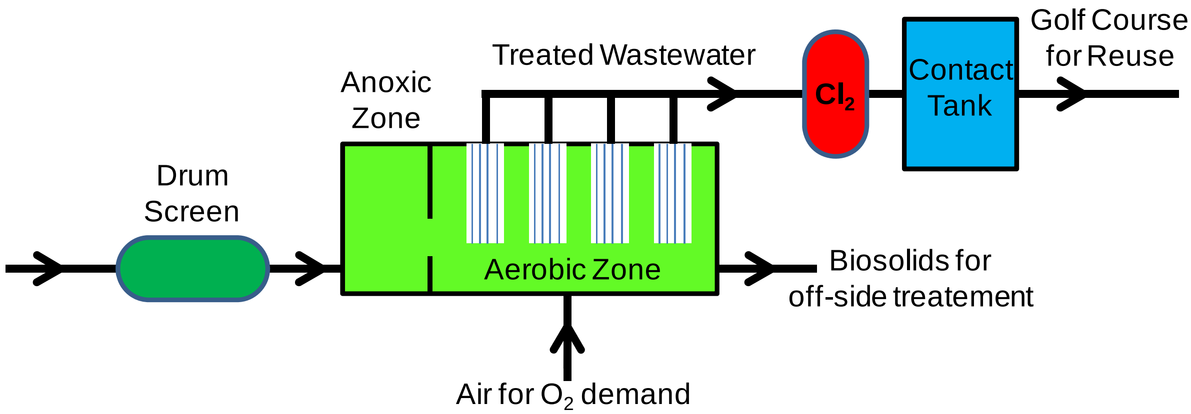
Figure 11-1: Decentralized Wastewater Treatment System for the Stonehurst Case Study



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 11-2 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.

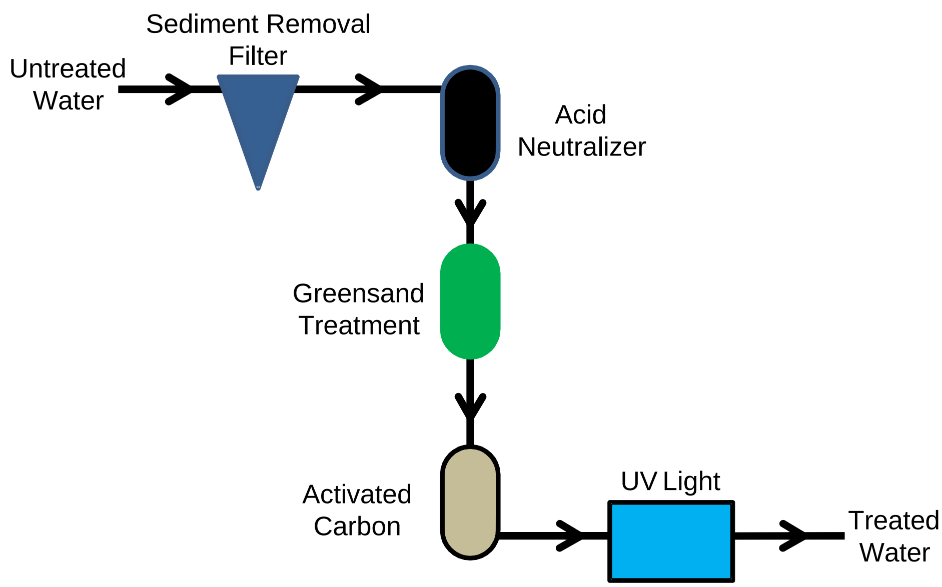
Figure 11-2: Decentralized Wastewater Treatment System for the Corona Case Study



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 11-3, 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 11-3: Point-of-Entry Water Treatment Case Study

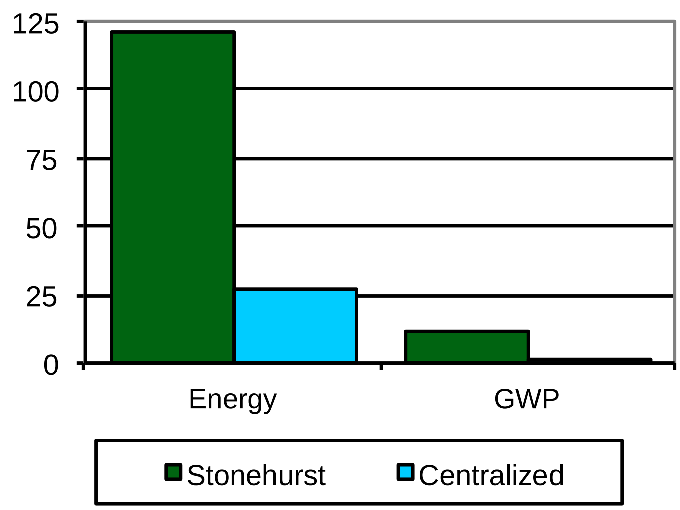


Task 11 Outcomes

Stonehurst Outcomes

Energy and GHG results for the Stonehurst decentralized wastewater system are presented in Figure 11-4. Previously published energy use and GHGs for a centralized wastewater utility in California (Stokes and Horvath 2010; see Chapter 10) are compared in Figure 11-4. 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 11-4: Energy and GHG Emissions Summary

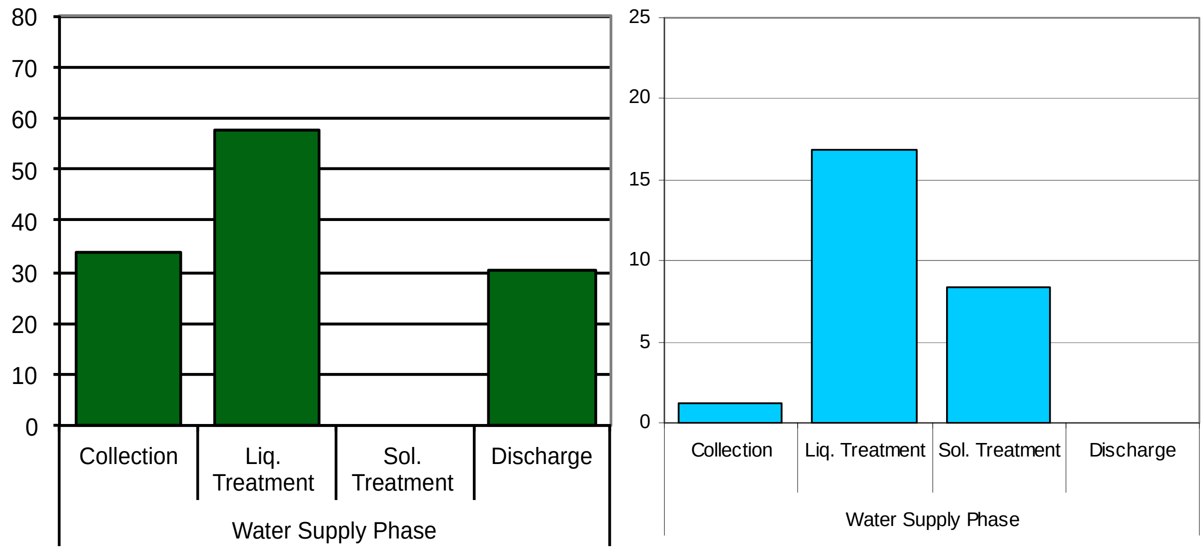


Values represent GJ for energy and Mg of GHGs per MG of treated wastewater.

Figures 11-5a-5c 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 11-5a, 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 11-5b 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 11-5c disaggregates energy use by activity and indicates that energy production (representing electricity generation) is the greatest contributor to the energy use for

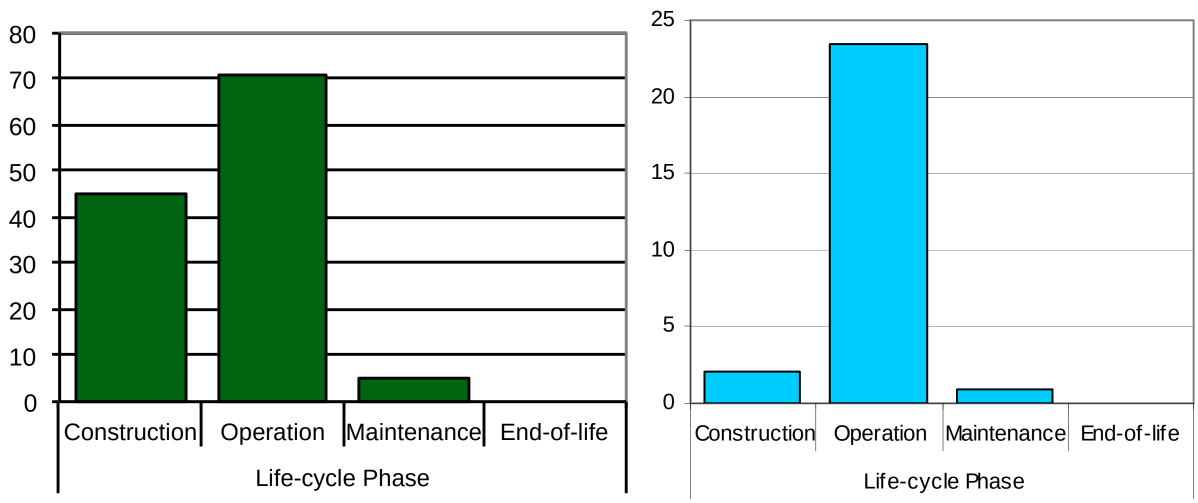
Stonehurst, followed by material production and equipment use. Figure 11-5c also shows that energy use for the Centralized system is fairly evenly divided between energy production and material production, while energy associated with equipment use is relatively minor.

Figure 11-5a: Water Supply Phase Energy Use



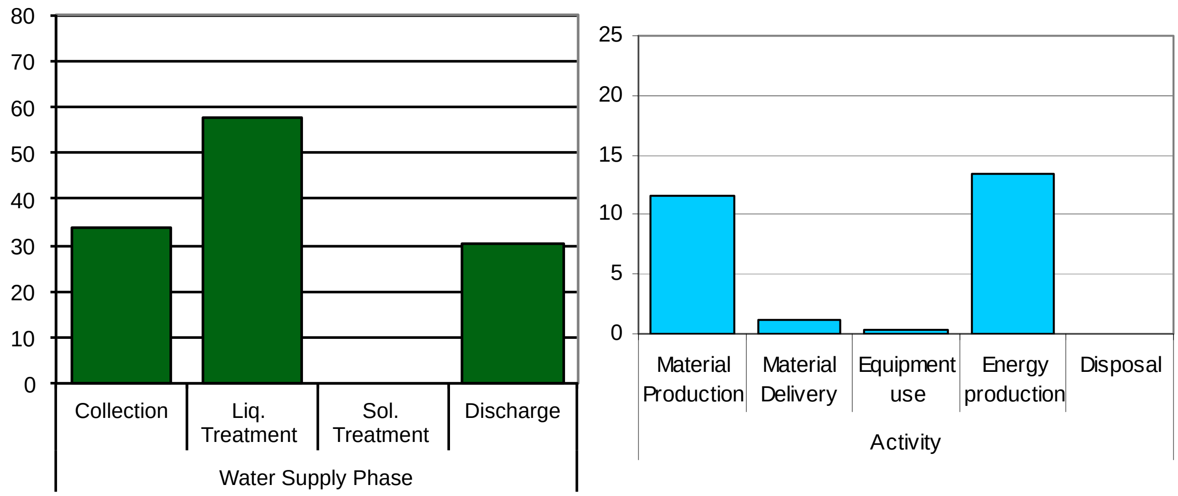
Energy use (GJ) per MG for Stonehurst (left) and centralized system (right). Note the difference in scale.

Figure 11-5b: 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.

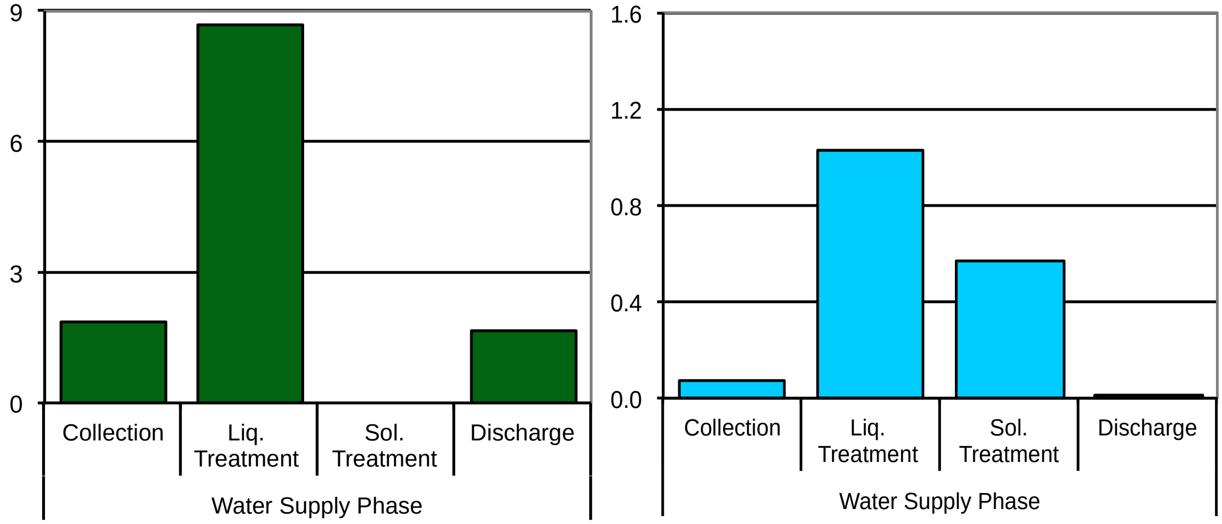
Figure 11-5c: Activity Phase Energy Use



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

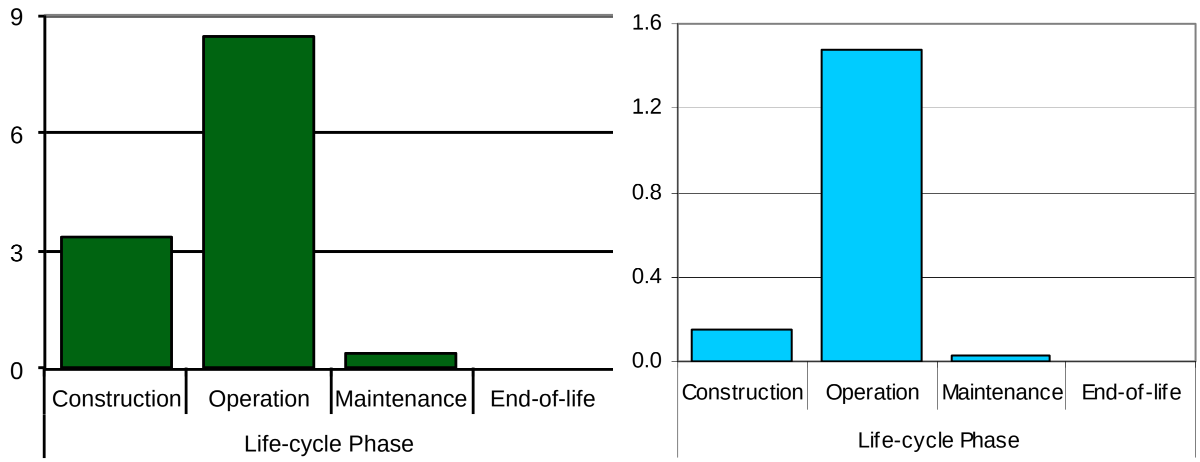
Figures 11-6a-6c disaggregate the GHG emissions for the Stonehurst and Centralized systems into wastewater phases, life-cycle phases, and activities, respectively. Figure 11-6a shows the GHG emissions from liquid treatment at Stonehurst are greatest, though GHG emissions from collection, solid treatment, 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 11-6b 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 11-6c, 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 11-6a: Water Supply Phase GHG Emissions



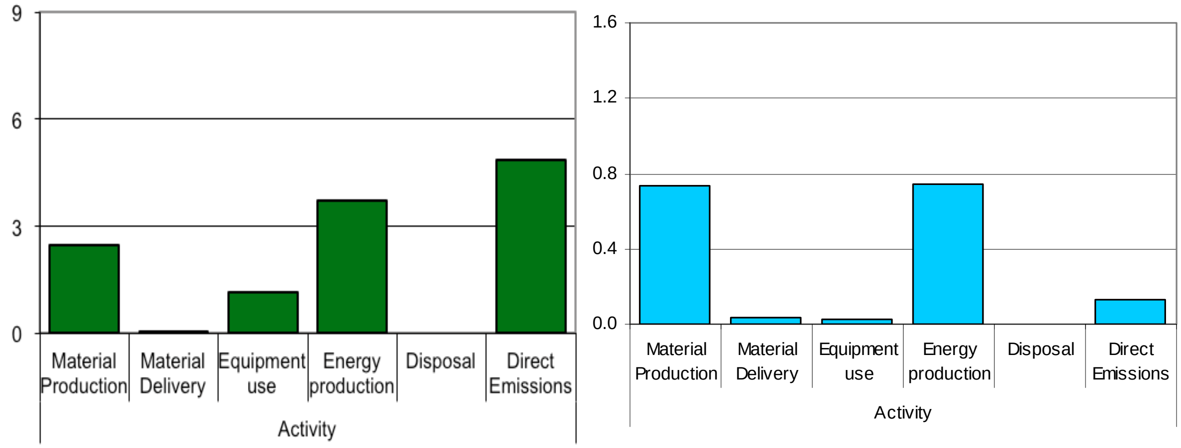
GHGs in Mg per MG for Stonehurst (left) and centralized system (right). Note the scale difference.

Figure 11-6b: Life-Cycle Phase GHG Emissions



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

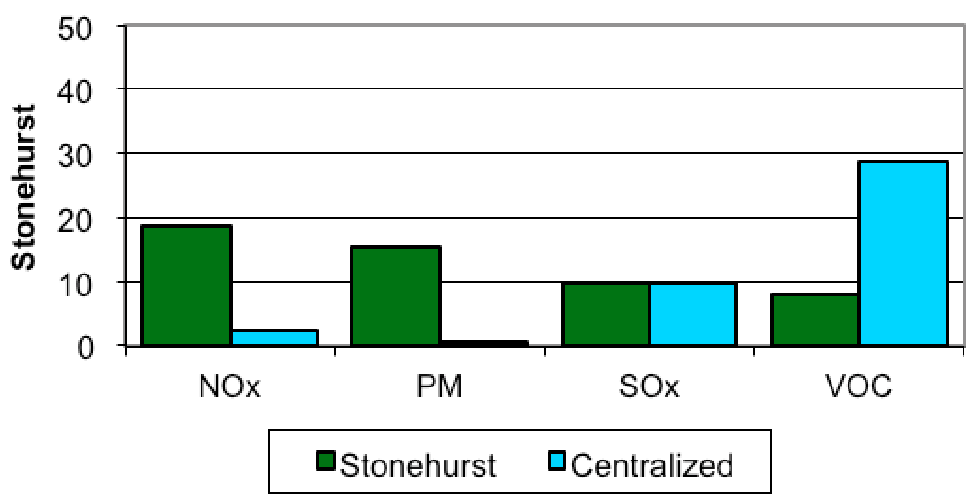
Figure 11-6c: GHG Emissions by Activity



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

Figure 11-7 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 11-7: Air Pollutant Emissions Summary

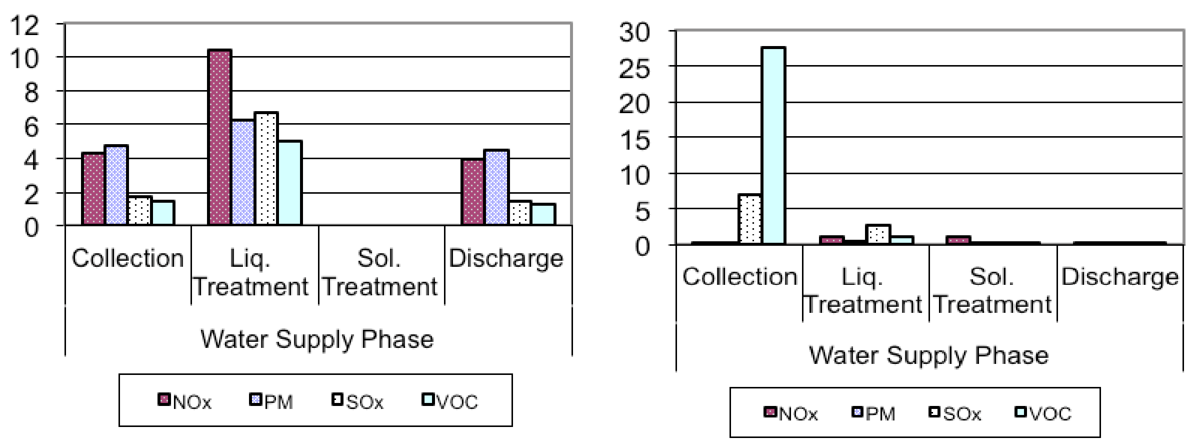


Air pollutant emissions for Stonehurst and centralized systems in kg per MG of treated wastewater.

Figures 11-8a-8c 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 11-8a 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 11-5a. 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.

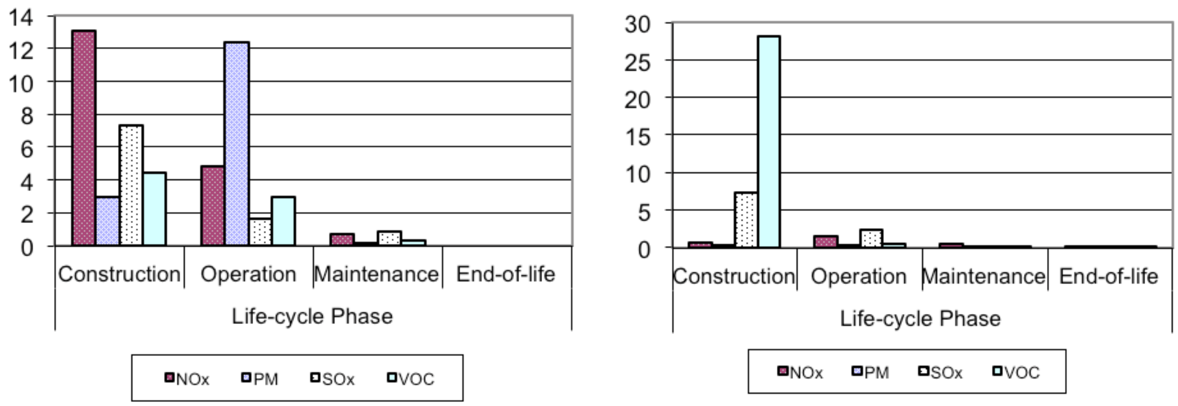
Figure 11-8b presents the distribution of air pollutants between different life-cycle phases and shows that most emissions occur during the construction and operation phases for both the Stonehurst and the Centralized plant. The distribution of air pollutants indicates that most of these emissions are 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 11-8c, 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 11-8a: Water Supply Phase Air Pollutant Emissions



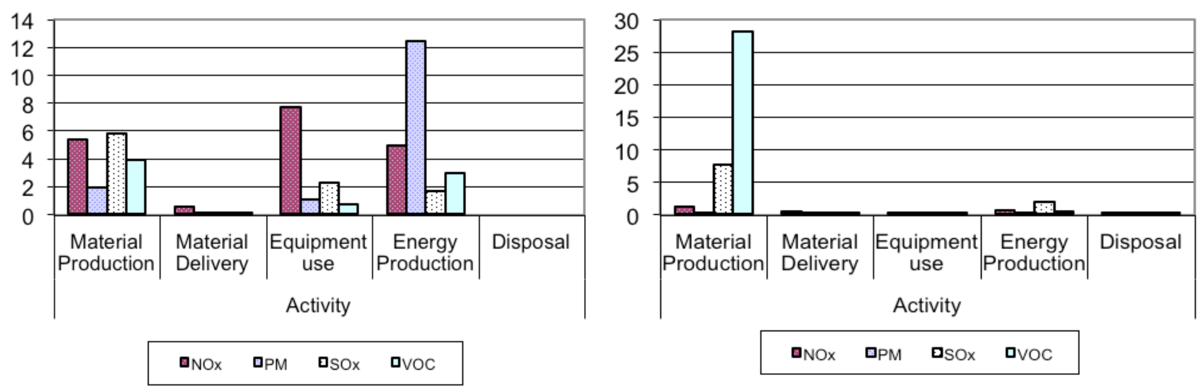
Air pollutant emissions (kg per MG) for Stonehurst (left) and centralized system (right). Note the difference in scale for Stonehurst and centralized treatment results.

Figure 11-8b: Life-Cycle Phase Air Pollutant Emissions



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

Figure 11-8c: Air Pollutant Emissions by Activity

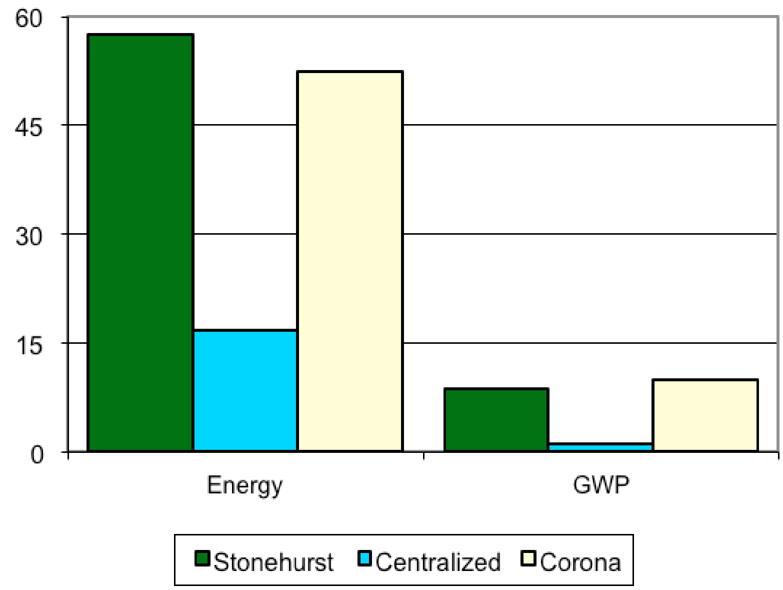


Air pollutant emissions (kg per MG) for Stonehurst (left) and centralized system (right). Note the difference in scale.

Corona Outcomes

Energy and GHG results for the Corona MBR treatment plant are presented in Figure 11-9. These results represent only the treatment phase of the wastewater treatment process (i.e. results do not include collection or disposal). Figure 11-9 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.

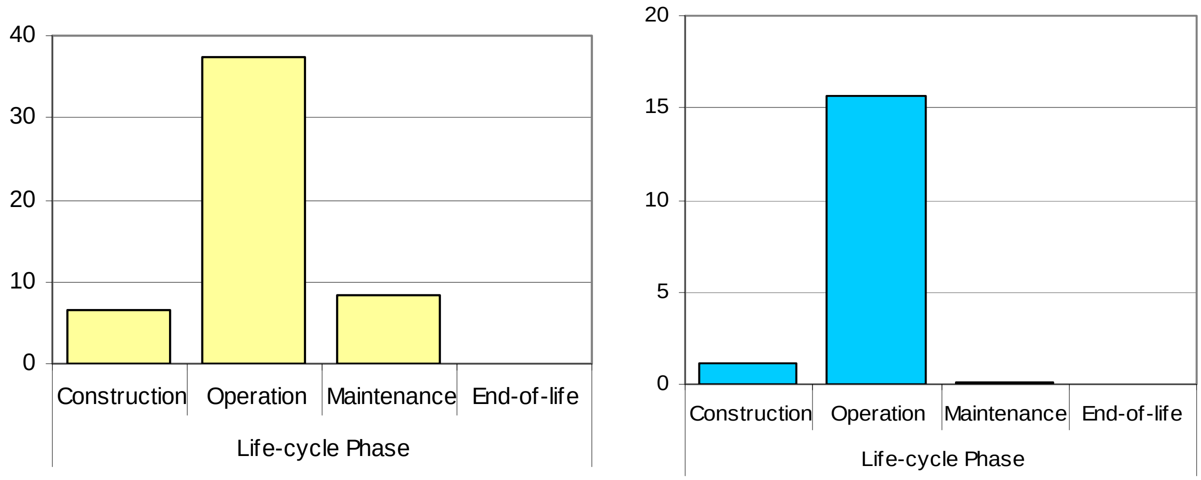
Figure 11-9: Treatment Phase Energy and GHGs Summary



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

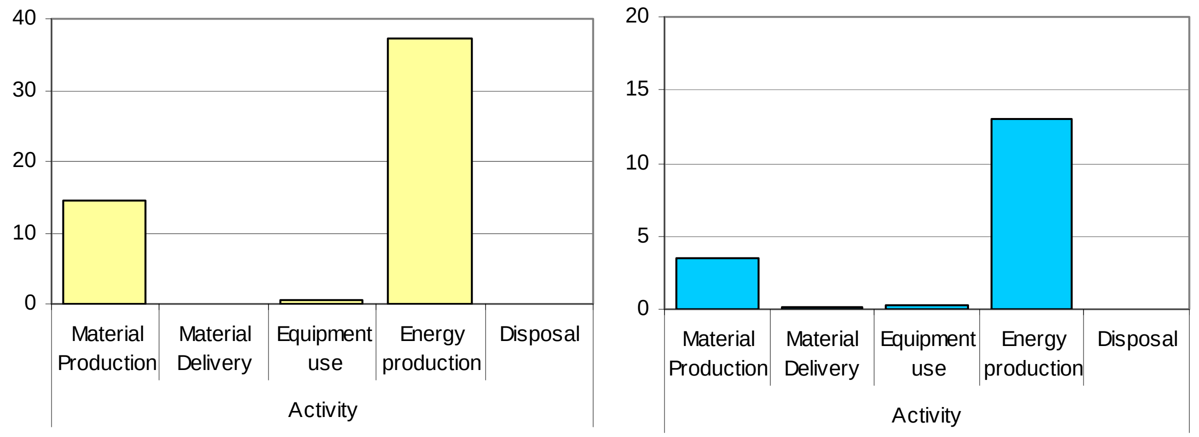
Figures 11-10a and 11-10b disaggregate the WWEST treatment phase energy results for both the Corona and Centralized treatment systems into life-cycle phases and activity, respectively. Figure 11-10a shows that operation stage demands the greatest energy for both the Corona and Centralized systems. The 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 11-10b 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 11-10a: Life-Cycle Phase Energy Use



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

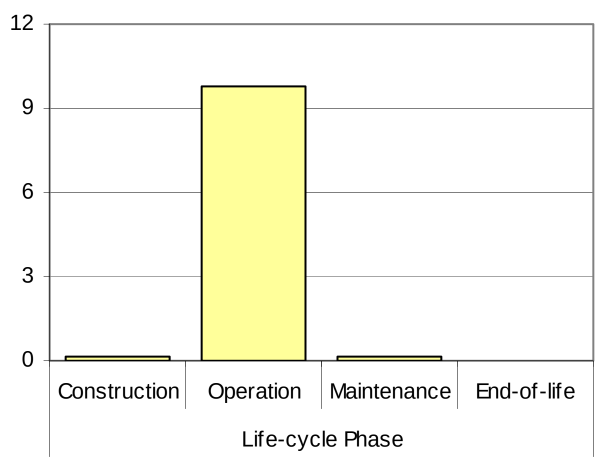
Figure 11-10b: Activity Phase Energy Use

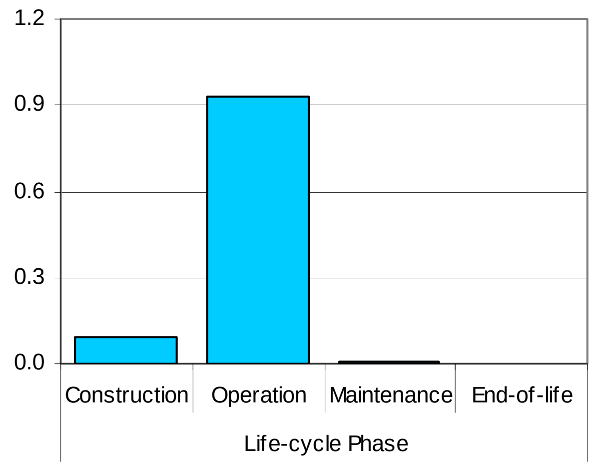


Treatment energy use (GJ per MG) of the Corona (left) and centralized system (right). Note the difference in scale.

Figures 11-11a and 11-11b disaggregate GHG emissions for treatment at the Corona and Centralized treatment systems into life-cycle phases and activity, respectively. Figure 11-11a 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 11-11b, 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.

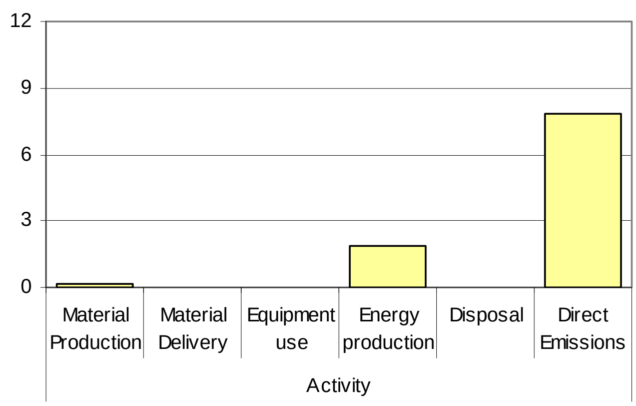
Figure 11-11a: Life-Cycle Phase GHG Emissions

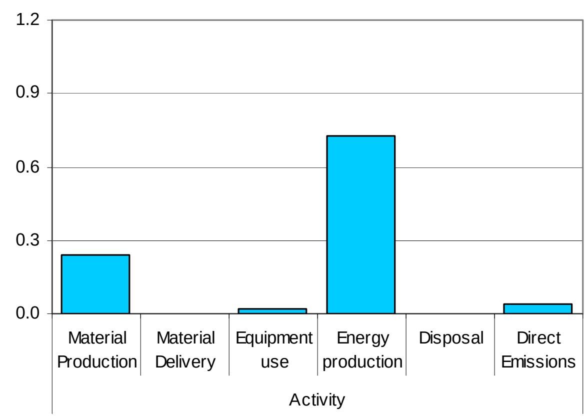




GHGs (Mg) per MGfor the treatment phase of the Corona (left) and centralized (right) wastewater system. Note the order-of magnitude difference in scale for Corona and Centralized results.

Figure 11-11b: GHG Emissions by Activity

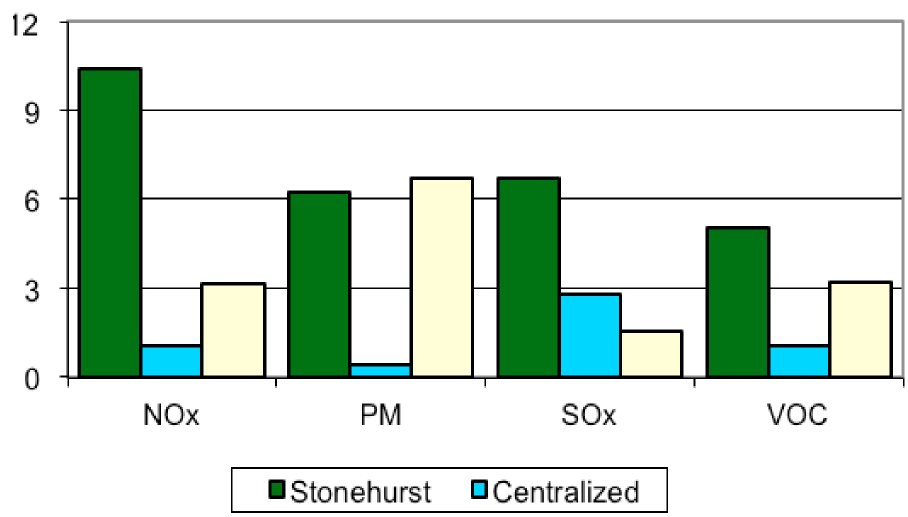




GHGs (Mg) for the treatment phase of the Corona (left) and centralized (right) system. Note the order-of magnitude difference in scale for Corona and Centralized treatment results.

Figure 11-12 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.

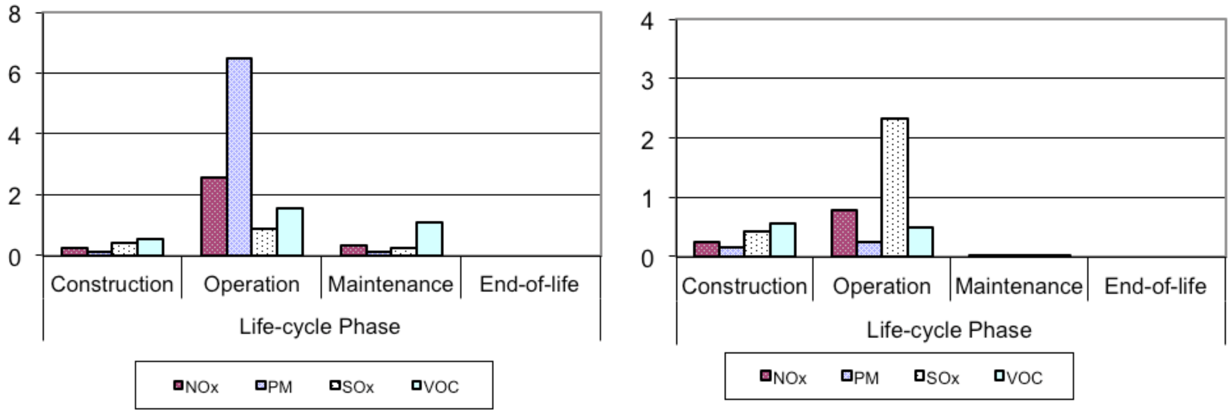
Figure 11-12: Treatment Phase Air Pollutant Emissions Summary



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

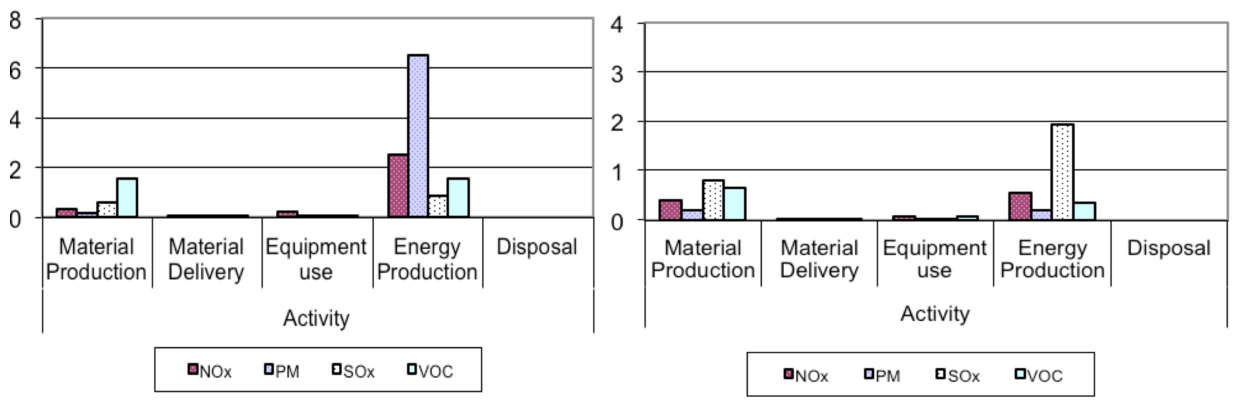
Figures 11-13a and 11-13b disaggregate the WWEST air pollutant emission results for the treatment phase at both the Corona and Centralized treatment plants into life-cycle phases and activity, respectively. Figure 11-13a presents the distribution of air pollutants between life-cycle phases. At the Corona 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 11-13b, 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 11-13a: 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 11-13b: Air Pollutant Emissions by Activity

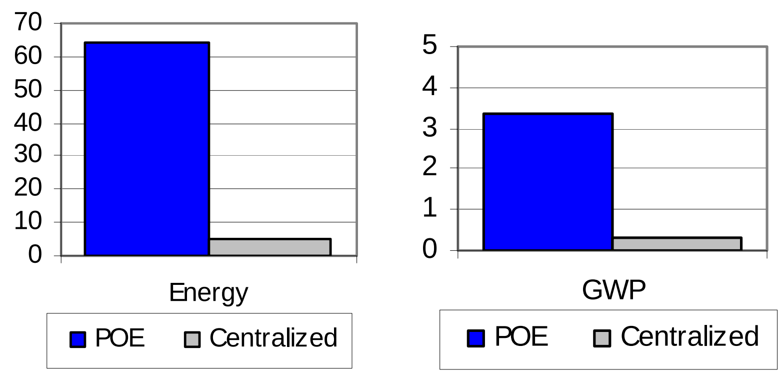


Air pollutant emissions (kg) per MG for the Corona (left) and Centralized (right) WWTPs. Note the difference in scale for Corona and Centralized treatment results.

Point-of-Entry Outcomes

Energy and GHG results for the POE water treatment case study are presented in Figures 11-14a and 11-14b. These results represent only the treatment phase (i.e. results do not include supply or distribution. Figures 11-14a and 11-14b 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.

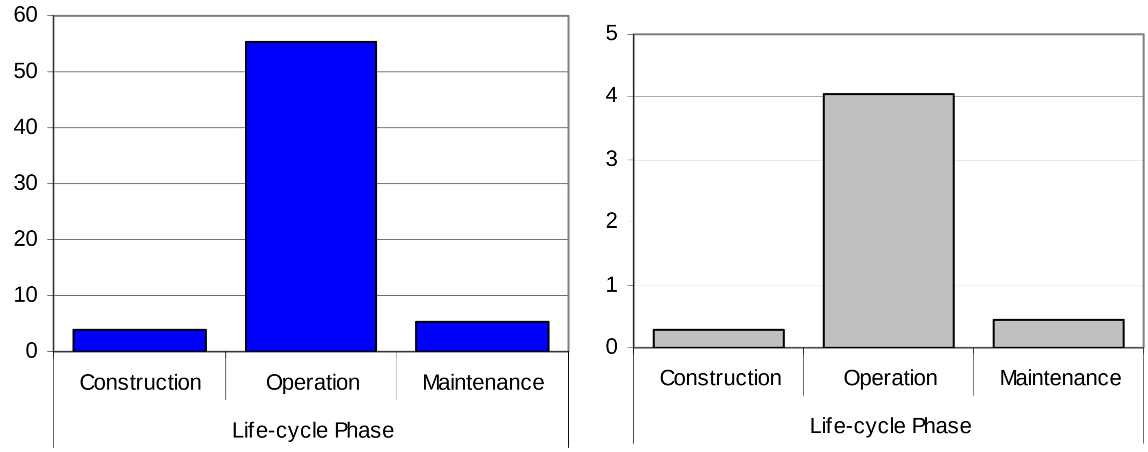
Figure 11-14a and 11-14b: Water Treatment Energy and GHGs Summary



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

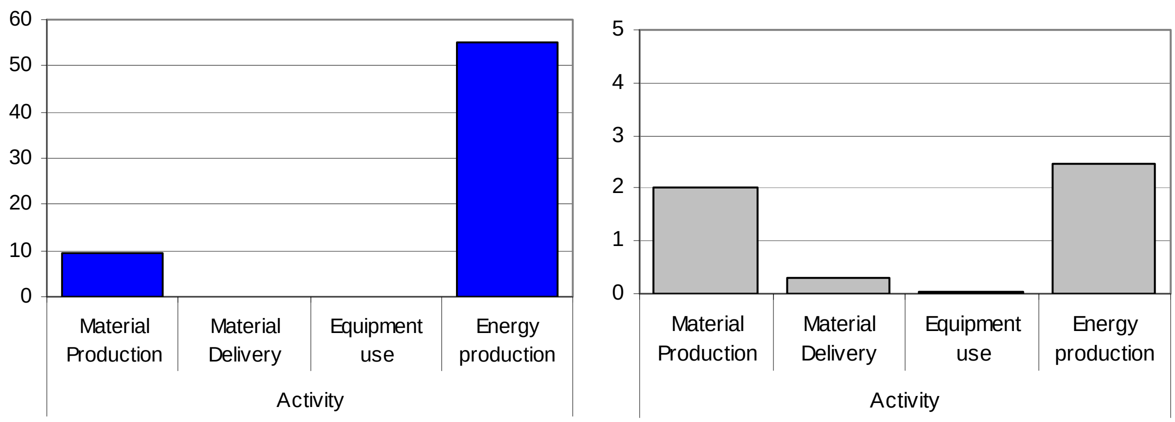
Figures 11-15a and 11-15b disaggregate the results for water treatment of both the POE case study and Centralized treatment plant into life-cycle phases and activity, respectively. While the overall energy use is significantly greater in the POE case study, Figure 11-15a shows a similar relative distribution 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 11-15b 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 11-15b 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 11-15a: 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 11-15b: Activity Phase Energy Use

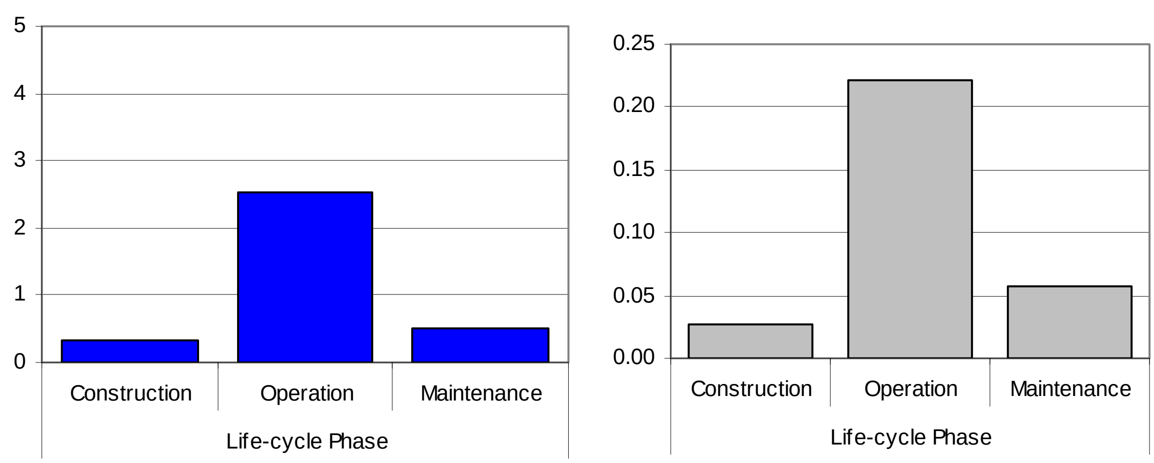


Energy use (GJ) per MG of the POE case study (left) and Centralized water treatment system (right). Note the scale difference.

Figures 11-16a and 11-16b disaggregate the GHG results for both the POE case study and Centralized water treatment systems into life-cycle phases and activity, respectively. Figure 11-16a shows that GHG emissions follow a similar trend to the life-cycle phase disaggregated energy use in Figure 11-15a, with most GHG emissions occurring during operation for both the POE and Centralized water treatment systems. Figure 11-16b, 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.

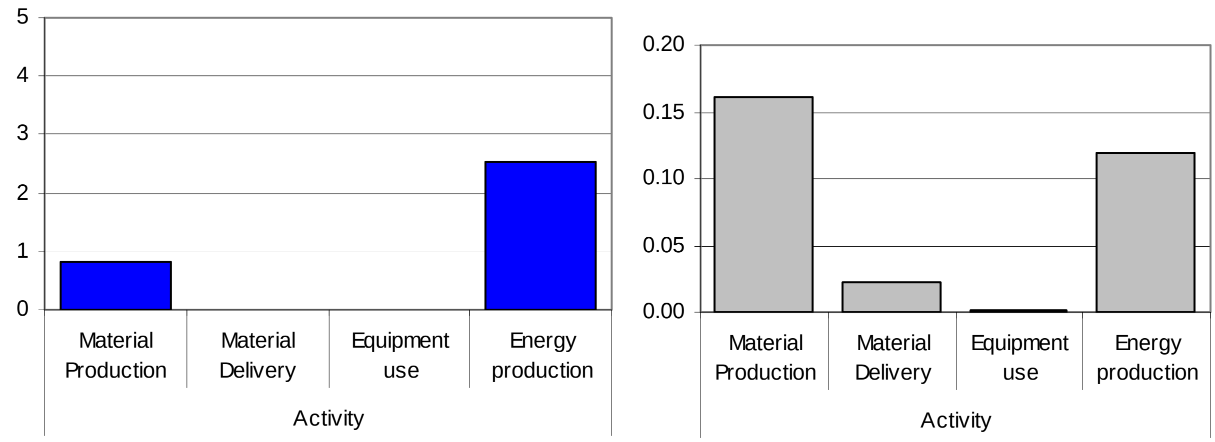
Figure 11-17 presents results for air pollutant emissions, specifically NO_x, PM, SO_x, and VOC, from both the POE case study and Centralized treatment systems. The air pollutant emissions from the POE case study are greater than the emissions from the Centralized treatment facility, though to a lesser 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 11-16a: Life-Cycle Phase GHG Emissions



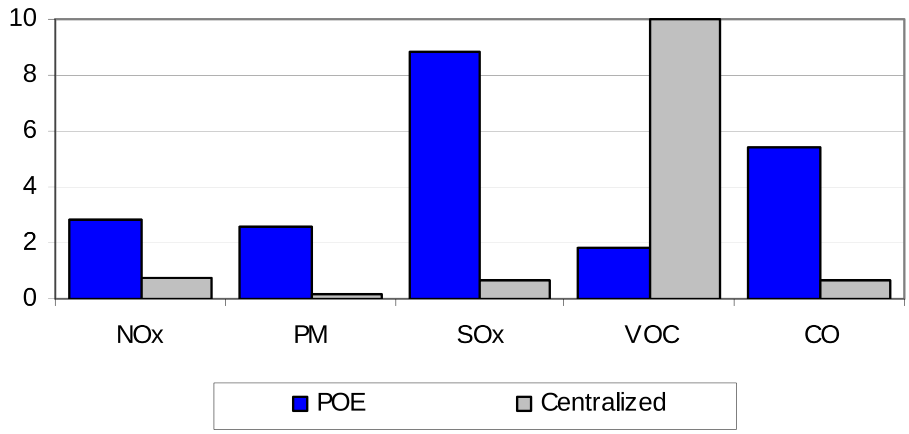
GHGs (kg) per MG for the POE case study (left) and Centralized water treatment system (right), separated by life-cycle phase. Note the difference in scale for POE and Centralized treatment results.

Figure 11-16b: 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.

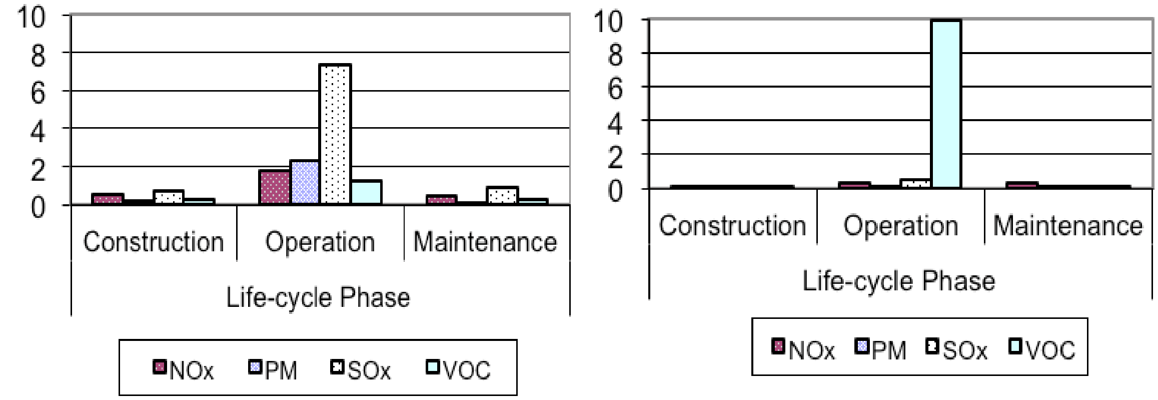
Figure 11-17: Water Treatment Air Pollutant Emissions Summary



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

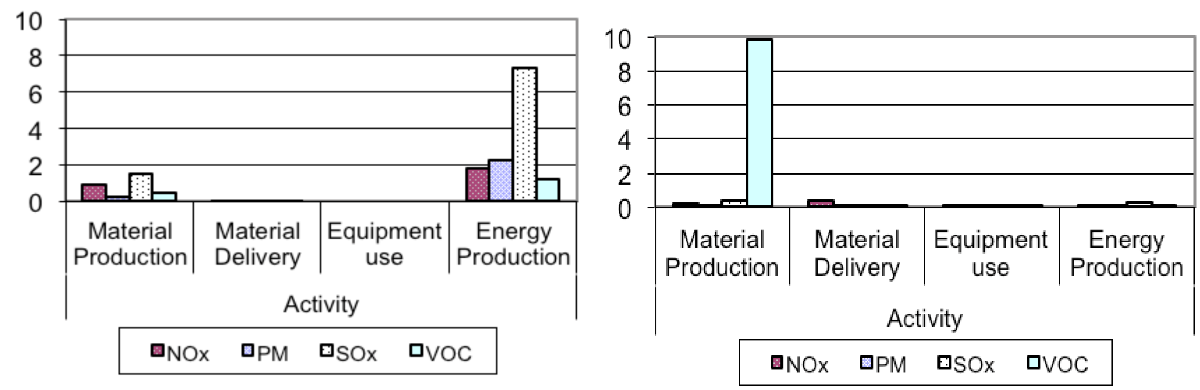
Figures 11-18a and 11-18b disaggregate the air pollutant emissions for both the POE and Centralized systems into life-cycle phases and activities, respectively. The distribution of air pollutants between different life-cycle phases confirms that most emissions occur during the operation phase for both 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 11-18a: 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 11-18b: 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.

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.

Project Outcomes

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

Deliverables

Table 12-1 summarizes the deliverables for the project, including which task or tasks are associated and where the deliverable can be located.

Table 12-1: 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.

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 12-2 summarizes these utilities and water sources analyzed.

Table 12-2: 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 12-3 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 13-3.

Table 12-3: California Utility Results Summary

Utility	**Energy (GJ/Mℓ)**	**GHGs (MJ/Mℓ)**	**NO_x (MJ/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

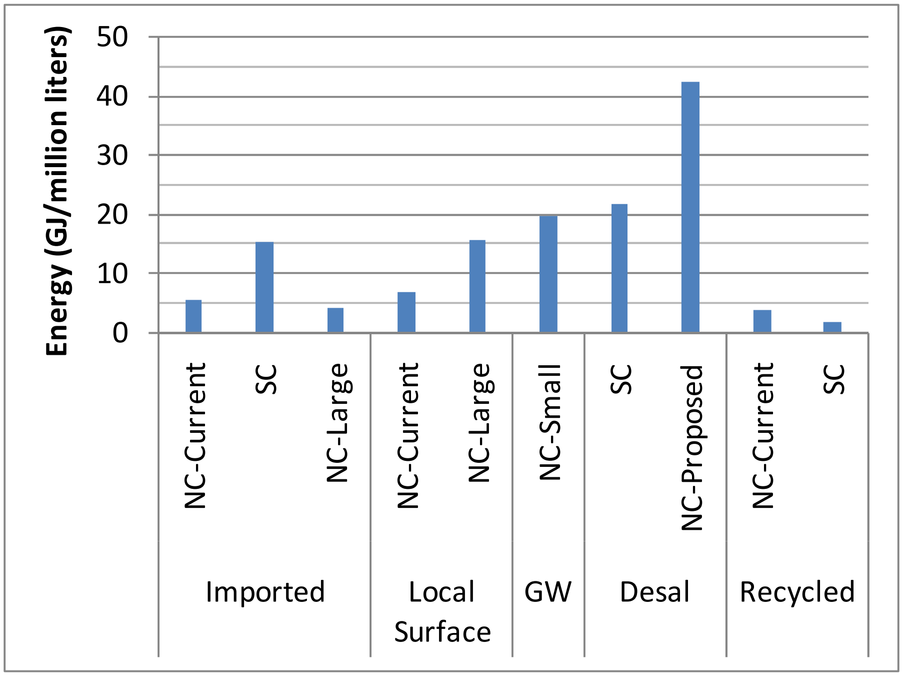
On a systemwide basis, the NC-Small utility consistently results in higher environmental burden, more than twice the other systems in most cases. Two factors may contribute to this outcome: 1) the significant amount of electricity needed to pump groundwater, the sole source of water for this system; 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 12-1 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 12-1: 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.

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 12-4 and 12-5 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 12-4: 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 12-5: 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

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.

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.

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 preferably 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 generally higher than alternative water supply.
- 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.

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.

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GLOSSARY/ACRONYMS

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

Appendix A: WEST and WWEST

Appendix A.1: WEST Tool **separate file**

Appendix A.1.1: WEST Manual

Appendix A.1.2: WEST Revision Logs

Appendix A.1.3: WEST Help Pages

Appendix A.1.4: WESTCalc Companion Tool separate file

Appendix A.2: WWEST Tool **separate file**

Appendix A.2.1: WWEST Manual

Appendix A.2.2: WWEST Revision Logs

Appendix A.2.3: WWEST Help Pages

Appendix A.1:
WEST Tool

This appendix is available as a separate volume,
Appendix_A.1_WEST_Tool.xls

Appendix A.1.1:
WEST Manual

WEST

Water-Energy Sustainability Tool

User’s Manual

Updated: August 1, 2010

Developed by: Dr. Jennifer Stokes and Prof. Arpad Horvath

Department of Civil and Environmental Engineering

University of California, Berkeley

http://www.ce.berkeley.edu/~horvath/west.html

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1.0 Acronyms and Abbreviations

The following summarizes the acronyms and abbreviations used in the manual and/or the WEST tool.

AF	Acre-foot	kg	Kilogram
Avg	Average	km	Kilometer
C or Con	Construction	kW	Kilowatt
Calc	Calculations	kWh	Kilowatt-hour
cf	Cubic feet	LCA	Life-cycle assessment
CH4	Methane	M or MMT	Maintenance
CO	Carbon monoxide	matl	Material
CO_2eq	Carbon dioxide equivalents	MD	Material delivery
Conv.	Conversions	Mech.	Mechanical
d	Day	memb	Membrane
D or Dis	Distribution	MG	Million gallons
Def	Default	Mg	Million grams
Dia.	Diameter	mi	Mile
Diso	Disposal	MJ	Megajoules
EFs	Emission factors	MMBTU	Million BTUs
EIO-LCA	Economic Input Output-based LCA	MP	Material production
ENR	Engineering News Record	mpg	Miles per gallon
EOL	End-of-life	MWh	Megawatt-hour
EP	Energy production	NO_x	Nitrogen oxides
equip.	Equipment	O or Op	Operation
EU	Equipment use	PM or PM_{10}	Particulate matter (<10 microns)
EXP	Explanatory Sheets	PVC	Polyvinyl chloride
ft	Feet	S or SUP	Supply
ft2 or ft^2	Square feet	SD	Sludge disposal
ft3 or ft^3	Cubic feet	sf	Square feet
g	gram	SO_x	Sulfur oxides
gal	Gallons	sq.	Square (for area)
gal/h	Gallons per hour	Sys	System
GHG	Greenhouse gas	T or Trt	Treatment
GWE	Global warming effect (units: CO_2eq)	UV	Ultraviolet
h or hr	Hour	VOC	Volatile organic compound
hp	Horsepower	WEST	Water-Energy Sustainability Tool
in.	Inch	WESTCalc	WEST companion tool for calculations
inf	Influent	Wksht	Worksheet
IPCC	International Panel on Climate Change	WWEST	Wastewater -Energy Sustainability Tool
ISO	International Organization for Standardization	yr	Year

2.0 What is WEST?

The Water-Energy Sustainability Tool (WEST) is an MS Excel-based tool which can determine some of the environmental effects of water system infrastructure and operation. Figure 1 shows the components of a water system which can be included in WEST. A companion tool, the Wastewater-Energy Sustainability Tool (WWEST), evaluates the effects of wastewater infrastructure and operation.

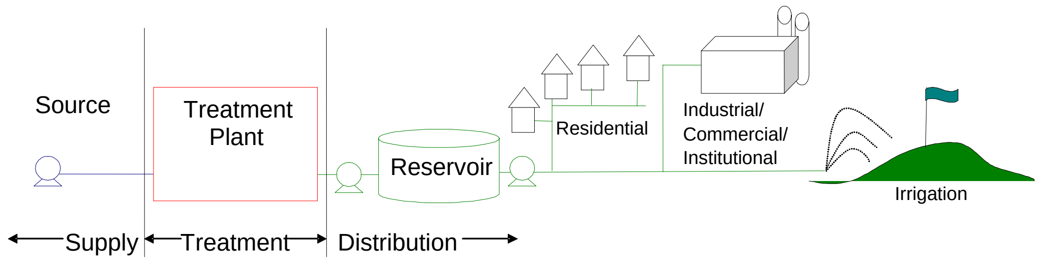


Figure 1: Water System Components [Stokes 2004]

WEST incorporates life-cycle assessment (LCA), a proven methodology for systematically quantifying cradle-to-grave material and energy inputs and air emissions. WEST can evaluate up to five sources of water at once (e.g., groundwater, reservoir, importation, desalination, and recycling), and/or compare components of the larger system (e.g., a new pipeline design, alternative treatment processes). The tool requires user input for the construction and maintenance phases, equipment use, and electricity consumption for a water supply system. Based on the input, WEST estimates air emissions. Environmental effects calculated include: energy consumption and emissions of greenhouse gases (GHGs, and CO_2 equivalents as the global warming effect [GWE]), nitrogen oxides (NO_x), particulate matter smaller than 10 microns (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOC). Select additional emissions to air and water are also available in the tools.

WEST provides the results according to the associated life-cycle phase (construction, operation, maintenance, or end-of-life), the water supply phase (supply, treatment, or distribution), life-cycle activity (material production, material delivery, equipment use, energy consumption, sludge disposal), and the water source or scenario (e.g., groundwater, reservoir, importation, desalination, and recycling). Alternative treatment options can be analyzed as separate scenarios as well (e.g., chlorination vs. ozone disinfection). The user will need to enter information about the differences in the material and energy use in the alternatives. Table 1 defines these categories with the exception of water sources or scenarios. These are user-defined. The activities are defined in additional detail in Section 4.0.

Phase/Category		Description
Life-cycle	Construction	Includes energy use & emissions from producing construction materials, treatment equipment, & energy used in initial installation, including supply chains; fuel use & emissions from construction equipment & delivery vehicles
	Operation	Includes energy & emissions from the collection, treatment, & discharge phases; energy generation offsets from treatment operation; fuel use & emissions from delivery & operational vehicles; energy use & emissions from producing chemicals & other routinely used materials (including supply chains); direct emissions from the treatment process
	Maintenance	Includes energy use & emissions from producing replacement parts for components with service lives shorter than the analysis period (including supply chain); fuel use & emissions from maintenance & delivery vehicles
	End-of-life	Includes fuel use & emissions for transporting & disposing of sludge; long term emissions, & energy generation offsets. Decommissioning water infrastructure contributes <0.01% to overall results [see documentation for Friedrich 2002], thus were not calculated
System	Supply	Transporting water from source to the treatment plant & related infrastructure
	Treatment	Ensuring effluent meets regulatory standards & necessary infrastructure
	Distribution	Transporting treated effluent to the consumer & required infrastructure
Activity	Material production	Quantifies materials used in the system & the energy/environmental effects of their manufacture & provision; primarily uses EIO-LCA supplemented with process-based LCA
	Material delivery	Assesses the energy used & emissions from transportation of materials by truck, train, ship, or airplane; uses process-based LCA
	Equipment use	Evaluates emissions & fuel use from operating non-transport construction equipment & maintenance vehicles; uses process-based LCA
	Energy production	Quantifies effects of electricity production & fuel production (e.g., gasoline, diesel) needed to operate vehicles; uses process-based LCA for electricity & EIO-LCA for fuel
	Sludge Disposal	Analyzes the effects of transporting & disposing of sludge; uses process-based LCA, except co-product offsets

Table 1: Category Definitions

WEST is designed to be used by water system designers, utility operators, civil engineers, consultants, and researchers. Users should have a working knowledge of water supply systems, data related to a real or hypothetical water system, and a desire to learn more about the environmental implications of their decisions.

3.0 What knowledge will I gain from using WEST?

WEST users may enter data about an existing, proposed, or hypothetical water system to determine the environmental effects of their decisions. The tools can inform decisions such as:

- WATER SOURCE SELECTION: To provide additional water, is it preferable to build a new pipeline, construct a new reservoir, desalinate water from a new source, or implement a recycled water program?
- MATERIAL SELECTION: For a particular pipeline installation, is steel or plastic pipe better for the environment?

- PROCESS SELECTION: Is it preferable to implement membrane or traditional filtration? Which disinfection method is more environmentally detrimental: chlorine, ozone, or ultraviolet light?
- ENERGY SOURCE SELECTION: What percentage of the environmental effects associated with my utility is associated with material production or electricity use? What if all our electricity came from solar power, how much would that reduce emissions?
- SUPPLIER SELECTION: How much can we reduce our environmental effects by purchasing from local suppliers? Using different chemicals?

This list of questions is not comprehensive but gives an idea of the types of issues that WEST can be used to evaluate. In addition, it is possible to customize WEST to get more specific results as needed. For example, custom calculations can be created to isolate the results for a particular treatment process and compare them to an alternate process or to utilize two different electricity mixes within the system.

4.0 What is the methodological basis of WEST?

WEST combines the power of two proven LCA approaches: process-based LCA and economic input-output analysis-based LCA (EIO-LCA).

Process-based LCA is outlined in the International Organization of Standardization's 14040 standards (ISO 1997)(Intergovernmental Panel on Climate 2006). In order to get specific and localized results, process-based LCA requires the practitioner to collect all needed data on energy and resource inputs and environmental outputs from any available sources (e.g., system operators, product manufacturers, industry experts, and available literature). As a result, it can be data-, time-, and cost-intensive. Some publicly- available sources provide process-based results for certain products. For example, PlasticsEurope provides information about manufacturing some plastic products and intermediary chemicals in Europe (PlasticsEurope 2010).

EIO-LCA was created by the Green Design Initiative at Carnegie Mellon University and can be accessed on-line at http://www.eiolca.net (Carnegie Mellon Green Design Institute 2007). It utilizes the U.S. economy's input-output matrix to comprehensively map the interactions between economic sectors and define product and service supply chains. These economic data are combined with publicly-available environmental data (e.g., resource consumption and environmental emission and waste data) When the user inputs a producer's expenditure in a particular economic sector, the model evaluates how much is spent directly in that sector and its supply chain and calculates the corresponding environmental emissions and wastes associated with the specified expenditures. EIO-LCA can be used to get an estimate of environmental effects based only on material and energy cost.

The structure of WEST is shown in Figure 2. WEST incorporates elements from both process-based LCA and EIO-LCA, as delineated in Table 1 and Figure 2. Generally, EIO-LCA is used to determine the effects of material production and process-based LCA is used to evaluate material delivery, equipment operation, and energy production.

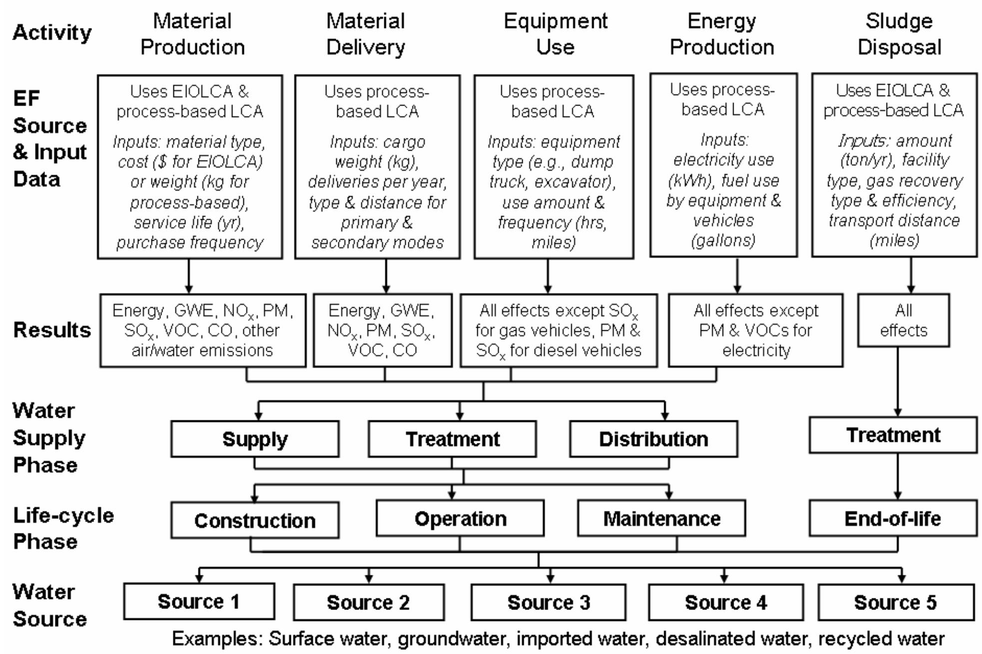


Figure 2: WEST Structure [adapted from (Stokes and Horvath 2006)

A hybrid LCA approach incorporates data from a variety of sources including: the on-line EIO-LCA tool for material production emissions, the Environmental Protection Agency's Emissions and Generation Resource Intregrated Database (E-GRID) (USEPA 2007) for electricity generation emissions and AP-42 standards for diesel engines (USEPA 1995), the Caterpillar and other manufacturers for equipment data (e.g., (Caterpillar Inc. 1996)), the California Air Resources Board's Off-Road Emissions Model for construction equipment emissions (California Air Resources Board 2002), published LCAs, and others. Detailed referencing is available in the background data sheets of the WEST tool and is described in (Stokes and Horvath 2006), (Stokes and Horvath 2009) and (Stokes and Horvath 2010) as well as in the final project report.

5.0 What are the "activities" analyzed in WEST?

As Figure 2 shows, WEST focuses on five activities that contribute to the environmental effects of a water system. Any or all of these can be used in a particular analysis. The five activities are: material production, material delivery, equipment use, energy production, and sludge disposal. Prior analyses have shown that the energy production and material production activities contribute most significantly to the environmental effect of conventional systems. For details, see (Stokes and Horvath 2006, 2010a, 2010b). Each activity is described further below.

5.1. Material Production

The Material Production activity estimates the impact of extracting, transporting, processing, and manufacturing materials from "cradle to gate", i.e., from the raw material extraction until the final product is ready to leave the door of the manufacturer. It can be used to analyze a wide variety of materials, including: concrete, pipe, pumps, electrical equipment, chemicals, steel tanks, and membranes. This module uses data from EIO-LCA in combination with some process-based information from databases from PlasticsEurope and/or GaBi, primarily for plastics and chemicals (GaBi 2005; PlasticsEurope 2010). The specific sources are cited within the tool on the "AirEFs" and "WaterEFs" worksheets. Table 2 shows the default materials included in WEST as well as related assumptions.

Material	Delivery Distance (km)	Service Life (yrs)	Process/ EIOLCA	Material	Distance (km)	Life (yrs)	Process/ EIOLCA	Material	Distance (km)	Life (yrs)	Process/ EIOLCA
Acid, carbonic	193	1	EIOLCA	Fans	515	15	EIOLCA	Pipe, ductile iron	257	75	EIOLCA
Acid, hydrochloric	193	1	EIOLCA	Ferric chloride	193	1	EIOLCA	Pipe, metal	257	75	EIOLCA
Acid, sulfuric	193	1	EIOLCA	Ferric sulphate	193	1	EIOLCA	Pipe, HDPE	257	50	EIOLCA
Acids, inorganic	193	1	EIOLCA	Ferrous sulphate (copperas)	193	1	EIOLCA	Pipe, plastic	257	50	EIOLCA
Activated carbon	322	1	EIOLCA	Fibers, manmade celluosic	1931	6	EIOLCA	Pipe, PVC	257	50	EIOLCA
Activated charcoal	322	1	EIOLCA	Fluid Power Equipment	515	1	EIOLCA	Pipe, stainless steel	257	75	EIOLCA
Adhesives	97	1	EIOLCA	Frames, metal	257	60	EIOLCA	Pipe, steel	257	75	EIOLCA
Adjustable frequency drives	1287	15	EIOLCA	Gaskets	97	2	EIOLCA	Pipe, vitrified clay	257	60	EIOLCA
Aggregate (filter media)	322	3	EIOLCA	Gasoline	322	1	EIOLCA	Plastic hose & belts	129	3	EIOLCA
Aggregate (not filter media)	193	100	EIOLCA	Generators	1609	15	EIOLCA	Plastic molding	193	15	EIOLCA
Alkalis	193	1	EIOLCA	Generators, turbine	1609	30	EIOLCA	Plastic products, misc.	193	15	EIOLCA
Alum	193	1	EIOLCA	Glass products	161	15	EIOLCA	Plastic resins	290	6	EIOLCA
Aluminum chloride	193	1	EIOLCA	Gravel aggregate	257	100	EIOLCA	Polyaluminum chloride	193	1	EIOLCA
Aluminum sulfate	193	1	EIOLCA	Gravel filter media	322	3	EIOLCA	Polyiron chloride	193	1	EIOLCA
Ammonia, aqueous	193	1	Process	HDPE resins	386	30	EIOLCA	Polymers	290	50	EIOLCA
Ammonium compnds	193	1	EIOLCA	Hydrated lime (dolomitic)	193	1	EIOLCA	Polypropylene	193	75	Process
Anthracite	4023	3	EIOLCA	Hydrogen peroxide	193	1	EIOLCA	PPE resins	290	75	EIOLCA
Asphalt	129	20	EIOLCA	Industrial equipment, electrical	515	100	EIOLCA	Pump intake screens	161	3	EIOLCA
Blowers	483	15	EIOLCA	Industrial equipment, general	515	25	EIOLCA	Pumps	515	15	EIOLCA
Brick	97	100	EIOLCA	Ion Exchange resins	3862	2	EIOLCA	Pumps, metering	644	5	EIOLCA
Building maintenance	97	5	EIOLCA	Iron forgings	257	100	EIOLCA	PVC resins	290	6	EIOLCA
Buildings; office, ind, & comm	322	60	EIOLCA	Jet fuel	322	1	EIOLCA	Rebar	193	100	EIOLCA
Calcium carbonate	193	100	EIOLCA	Joint compounds	161	60	EIOLCA	Reinforced concrete	193	100	EIOLCA
Calcium hypochlorite	193	5	EIOLCA	Laboratory equipment	515	8	EIOLCA	Riprap	241	100	EIOLCA
Calcium oxide	193	1	EIOLCA	L&scaping	129	12	EIOLCA	Rubber hose & belts	97	2	EIOLCA
Carbon dioxide	193	1	EIOLCA	Light bulbs & tubes	97	2	EIOLCA	Rubber, synthetic	97	20	EIOLCA
Cardboard	97	1	EIOLCA	Light fixtures & equipment	322	15	EIOLCA	S& filter media	322	3	EIOLCA
Cartridge filters	322	2	EIOLCA	Lime (Calcium hydroxide)	193	1	EIOLCA	Sealants	97	5	EIOLCA
Caustic soda	193	1	Process	Limestone	241	1	EIOLCA	Sealing devices	97	3	EIOLCA
Chemicals, general	193	1	EIOLCA	Lubricants	193	12	EIOLCA	Soda ash	193	1	EIOLCA
Chemicals, industrial	193	1	EIOLCA	Lumber	129	40	EIOLCA	Sodium aluminate	193	1	EIOLCA
Chemicals, inorganic oxidizers	193	1	EIOLCA	Magnesium hydroxide	193	1	EIOLCA	Sodium bicarbonate	193	1	EIOLCA
Chemicals, water treatment	193	1	EIOLCA	Magnesium oxide	193	1	EIOLCA	Sodium bisulfite	193	1	EIOLCA
Chloramine	193	1	EIOLCA	Membrane, cellulose acetate	1931	6	EIOLCA	Sodium hypochlorite	193	1	EIOLCA
Chlorine	193	1	Process	Membrane, PSU	1931	6	EIOLCA	Sodium metabisulfite	193	1	EIOLCA
Clay (as construction material)	257	60	EIOLCA	Membrane, PVDF	1931	6	EIOLCA	Sodium sulfate	193	1	EIOLCA
Clay tile, structural	97	60	EIOLCA	Meters, flow	1287	15	EIOLCA	Sodium sulfite	193	1	EIOLCA
Coal	4023	60	EIOLCA	Molding & trim, metal	257	60	EIOLCA	Sodium thiosulfate	193	1	EIOLCA
Compressors	515	10	EIOLCA	Mortar	322	40	EIOLCA	Steel forgings	257	100	EIOLCA
Computers	257	4	EIOLCA	Motors	515	15	EIOLCA	Steel railings	161	50	EIOLCA
Concrete additives	129	100	EIOLCA	Natural Gas	193	1	EIOLCA	Steel, raw	257	100	EIOLCA
Concrete block	193	100	EIOLCA	Office furniture, non-wood	161	15	EIOLCA	Street maintenance	161	10	EIOLCA
Concrete products, other	386	100	EIOLCA	Office furniture, wood	161	15	EIOLCA	Streets	225	20	EIOLCA
Concrete, precast	386	100	EIOLCA	Oil & lubricants	97	1	EIOLCA	Sulfur dioxide	193	3	EIOLCA
Concrete, ready-mixed	129	100	EIOLCA	Oil fuel	193	1	EIOLCA	Tanks, bolted steel	1287	50	EIOLCA
Construction equipment	290	10	EIOLCA	Oxygen	193	1	EIOLCA	Tanks, other steel	1287	50	EIOLCA
Controls	386	15	EIOLCA	Ozone	0	1	EIOLCA	Trucks, Industrial	515	10	EIOLCA
Crude petroleum	644	10	EIOLCA	Packing devices	483	3	EIOLCA	Turbines	1931	30	EIOLCA
Diesel	322	1	EIOLCA	PAN- fiber reinforced products	193	1	EIOLCA	Valves & fittings, metal	257	15	EIOLCA
Doors, metal	257	40	EIOLCA	Petroleum products	161	1	EIOLCA	Valves & fittings, plastic	257	10	EIOLCA
Drilling mud	193	1	EIOLCA	PEI	1931	1	EIOLCA	Wood	129	50	EIOLCA
Electrical equipment	386	15	EIOLCA	Pipe sealing compounds	161	30	EIOLCA	Zinc orthophosphate	193	1	EIOLCA
Electrical wire	97	1	EIOLCA	Pipe, cast iron	257	75	EIOLCA	Tanks, redwood	129	50	EIOLCA
Electronics, office	322	4	EIOLCA	Pipe, concrete	257	75	EIOLCA	Wood pump stations	129	50	EIOLCA
Epoxies	97	5	EIOLCA	Pipe, DI- lined/coated	257	75	EIOLCA				

Table 2: Material Summary and Default Data

Service lives of materials are also listed in Table 2. The calculations use this information to determine how many times each material will be purchased during the analysis period. For example, if the analysis period is 25 years, pumps with a service life of 15 years will be purchased once at the time of construction and once at the end of the service life. Two-thirds of the impacts for the second purchase will be classified in the maintenance category because ten of the fifteen years of the pump's life is in the analysis period. If the service life is longer than the analysis period, the material will only be purchased once at the time of construction.

5.2. Material Delivery

This activity calculates the impacts of transporting materials from the point of manufacture to the point of final use. The following modes of transportation can be evaluated: local truck, long-distance truck, train, ship, and plane. The user can evaluate a primary and secondary mode of transportation. The secondary mode can be used when transportation is used serially, i.e., when product is off-loaded from a train to a local truck. Default delivery distances exist for all materials but should be reviewed and edited by the user.

5.3. Equipment Use

The Equipment Use section calculates the tailpipe emissions from construction equipment, maintenance vehicles, and personal-use vehicles. Some equipment that can be analyzed include: concrete mix truck, small and large excavator, backhoe loader, wheel loader, vibratory roller compactor, grader, dozer, dump truck, forklift, crane, generator, tanker truck, paver, sedan, and pickup truck. Personal-use vehicles are included to analyze passenger cars included in the utility's fleet, if applicable, and can also be used to analyze the effects of commuting if the user is interested.

5.4. Energy Production

Energy production includes the effects of electricity generation, natural gas combustion, and fuel production for gasoline and diesel. Natural gas is used by water utilities to operate pumps and turbines, for example. Fuels are used in on-site equipment like generators or in vehicles. For electricity consumption, the user can select whether they will use direct emissions (i.e., smokestack) or life-cycle emissions which also includes the supply chain. The user can also choose between emission factors (EFs) for the national average energy mix, state-specific energy mix, or a custom energy mix which uses a combination of coal, oil, natural gas, other fossil fuels (e.g., blast furnace gas, coke oven gas, methanol), hydroelectric, nuclear, biomass, wind, geothermal, and solar. In addition, the user can enter custom EFs for their site. Natural gas combustion EFs are also available and can be customized.

The effects of producing fuels for vehicles and equipment are included as well. The emissions associated with fuel production are calculated automatically based on inputs to the equipment use worksheet. No additional data must be entered for this category. However, the EFs can be edited by the user, if desired.

5.5. Sludge Disposal

Sludge disposal includes the effects of collecting, transporting, and disposing of sludge produced in the treatment process. The scenario assumes a wheel loader will be used to collect and move the soil onsite and that all sludge will be handled twice, once at the utility location and once at the landfill. A dump truck is assumed to be used to transport waste. The user can define the delivery distance and the nature of the disposal facility. WEST contains EFs for landfills and incinerators. The user can edit these EFs or enter EFs for an alternative disposal scenario.

6.0 What data are needed to use WEST?

Figure 2 summarizes the types of input data needed to analyze each activity included in the WEST tool. Not all users will be interested in using all aspects of the tool. Users should determine which components and activities are of most interest to them and focus their time and resources on obtaining the necessary data to complete those components. For example, a utility may only be interested in understanding the GHG emissions associated with electricity production and will therefore be able to ignore data entry for all but the general information and energy production sheets. If a utility is also interested in analyzing the effects of their treatment chemical consumption, data about their annual chemical consumption should also be entered on the material production page. If the utility wants a more comprehensive analysis, the user may choose to include an inventory of capital materials in the entire system, or perhaps for a particular aspect of the system (e.g., filtration equipment), and will need to input costs for that equipment in the tool.

A companion tool, WESTCalc, is available to help the user estimate material production and equipment use needed to construct large infrastructure projects, including aqueducts, dams, treatment plants, pump stations, and distribution networks. The tool includes cost data in 1997 dollars, the correct units for entry into EIOLCA, and unit weights for common materials. The user can enter pipe lengths, treatment equipment size, or pump number and capacity and automatically convert it into the units needed for entry into WEST. In addition, a spreadsheet to guide data gathering is available for users who wish to do a comprehensive inventory of all system infrastructure.

7.0 How do I start using WEST?

The following sections describe the WEST tool and are intended to help the reader utilize the tool, but do not fully detail all the background assumptions, data sources, calculations and references. If you are interested in more specific information included in the tool, including equations, please refer to:

- the WEST documentation included in the tool,
- the final project report to the California Energy Commission for Project MR-06-08 (available early 2011 on the Energy Commission's website);
- Stokes, J. and A. Horvath (2006). "Life cycle energy assessment of alternative water supply systems." International Journal of Life Cycle Assessment **11**(5): 335-343.
- Stokes, J. R. and A. Horvath (2009). "Energy and Air Emission Effects of Water Supply." Environmental Science & Technology **43**(8): 2680-2687.
- Stokes, J. and A. Horvath (2010). "Life-cycle Assessment of Urban Water Provision: A Tool and Case Study in California." Journal of Infrastructure System **In Print**.

There are five types of worksheets in WEST: entry, results, explanatory, calculations, and background worksheets. Each worksheet type is described in the following sections.

7.1. Entry Worksheets

The tool takes the user through a series of input worksheets to gather data about:

- The general system (e.g., location, sources of water, facilities such as treatment plants)
- Initial construction and maintenance materials as well as material transportation distances and modes
- On-site construction equipment (e.g., excavator, loader)
- Electricity consumption.

For each data entry page, a list of required data needed to complete the page is provided. A sample list of optional data for a utility is also provided.

The color convention for data entry cells in WEST are as follows:

- The user should enter data in the PURPLE cells.
- The user should select an option from a drop-down menu in the GREEN cells.
- WEST automatically reads in data from elsewhere in the tool in YELLOW cells; the user can update as needed. These cells are typically locked so the user does not inadvertently change the data.
- WEST automatically calculates values in TAN cells; the user can update as needed. These cells are typically locked so the user does not inadvertently change the data.

Hyperlinks (blue underlined text) refer to cells which describe the data which should be entered into the cell and, if relevant, provide equations used.

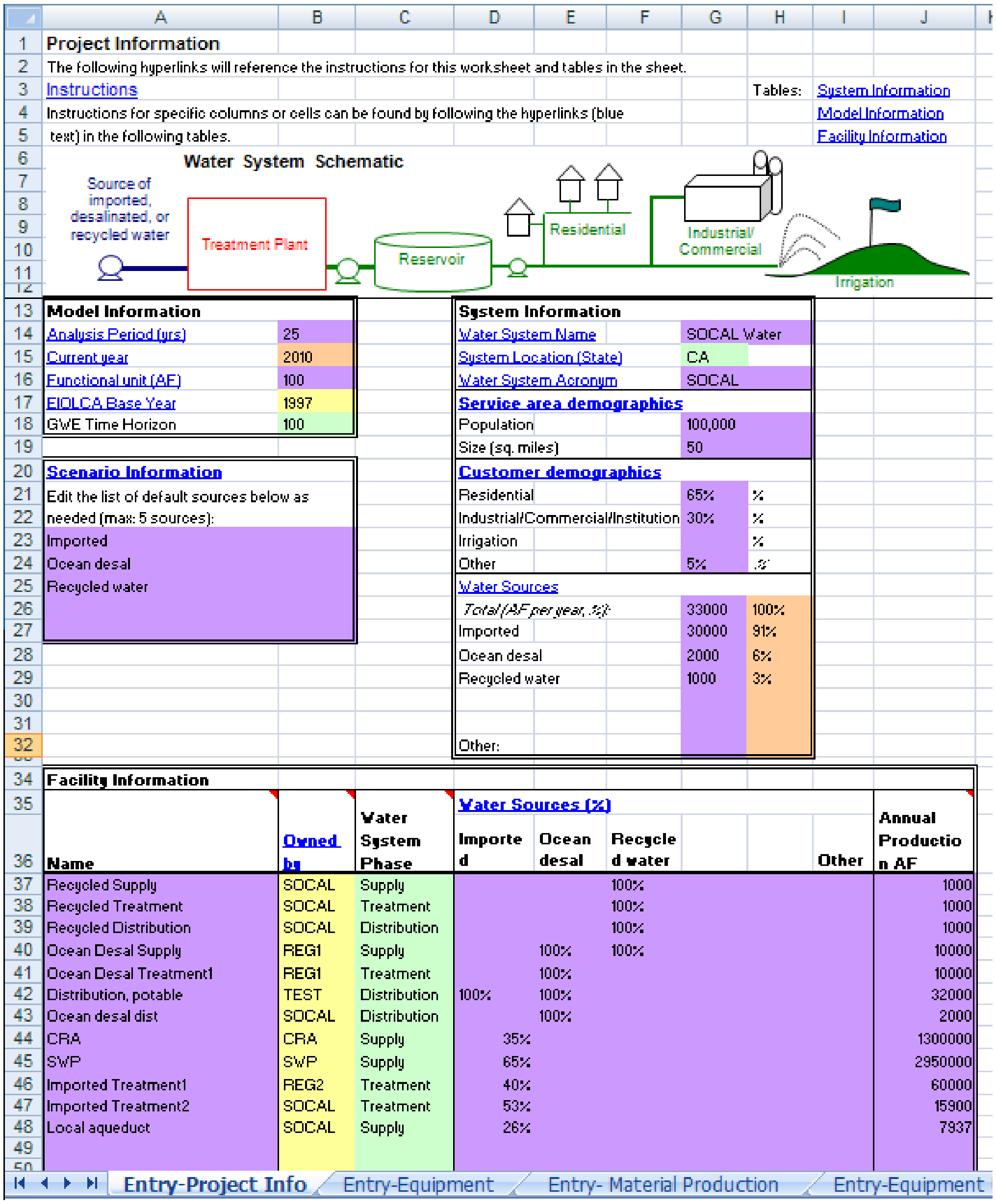
TIP: DO **NOT** SORT data or DELETE lines out of entry tables. Data can be deleted out of specific lines but do not change the structure of the table itself. This will cause calculation errors.

7.1.1. General Data Entry

Required data: Analysis period, functional unit, GWE time horizon, scenario name, system name, annual water production from water sources, facility information

Optional data: System acronym, service area demographics, customer demographics

Figure 3 shows the Project Information worksheet which collects the general inputs about the water system. The sheet is filled in with hypothetical data for demonstration purposes. Each cell is described below.



Project Information

The following hyperlinks will reference the instructions for this worksheet and tables in the sheet.

Instructions

Instructions for specific columns or cells can be found by following the hyperlinks (blue text) in the following tables.

Tables: System Information, Model Information, Facility Information

Water System Schematic

Model Information	
Analysis Period (yrs)	25
Current year	2010
Functional unit (AF)	100
EIOLCA Base Year	1997
GWE Time Horizon	100

Scenario Information
Edit the list of default sources below as needed (max: 5 sources):
Imported
Ocean desal
Recycled water

System Information		
Water System Name	SOCAL Water	
System Location (State)	CA	
Water System Acronym	SOCAL	
Service area demographics		
Population	100,000	
Size (sq. miles)	50	
Customer demographics		
Residential	65%	%
Industrial/Commercial/Institution	30%	%
Irrigation		%
Other	5%	.%
Water Sources		
Total (AF per year, %)	33000	100%
Imported	30000	91%
Ocean desal	2000	6%
Recycled water	1000	3%
Other:		

Facility Information

Name	Owned by	Water System Phase	Water Sources (%) Imported	Ocean desal	Recycled water		Other	Annual Production AF
Recycled Supply	SOCAL	Supply			100%			1000
Recycled Treatment	SOCAL	Treatment			100%			1000
Recycled Distribution	SOCAL	Distribution			100%			1000
Ocean Desal Supply	REG1	Supply		100%	100%			10000
Ocean Desal Treatment1	REG1	Treatment		100%				10000
Distribution, potable	TEST	Distribution	100%	100%				32000
Ocean desal dist	SOCAL	Distribution		100%				2000
CRA	CRA	Supply	35%					1300000
SWP	SWP	Supply	65%					2950000
Imported Treatment1	REG2	Treatment	40%					60000
Imported Treatment2	SOCAL	Treatment	53%					15900
Local aqueduct	SOCAL	Supply	26%					7937

Entry-Project Info | Entry-Equipment | Entry- Material Production | Entry-Equipment

Figure 3: ***Entry- Project Information*** **Worksheet**

Model information table:

- ANALYSIS PERIOD: Defines the time period over which analysis occurs. The analysis period should be selected appropriately for the materials being analyzed. If capital materials are analyzed, an analysis period of 20-30 years may be used to represent the planning horizon for the facility. The user may also reasonably select an analysis period equivalent to the longest service life in the system (e.g., up to 100 years for concrete materials). Regardless of the analysis period chosen, the WEST calculations will account for additional purchase of materials with service lives shorter than the analysis. Purchases of materials with services lives longer than the analysis period are discounted accordingly. If the user is only interested in consumable materials such as electricity, fuels, and chemicals, the selection of an analysis period is irrelevant and an analysis period of 1 year may be appropriate. This is a required input.

- ANALYSIS YEAR: Defines the year of the analysis. It is used as the default year of purchase for materials in the system for cost discounting. The default value is the current year.
- FUNCTIONAL UNIT: Defines the volume of water to which all results will be normalized. The units are acre-feet. The user may select a round functional unit (i.e., one AF) or one that is significant in the analysis (i.e., the amount of water processed annually by the facility being analyzed or the expected growth in water demand in the next 25 years). This is a required input.
- EIO-LCA BASE YEAR: Informs the user of the based year used for EIOLCA EFs. When materials use EIO-LCA EFs to estimate their material production effects, the costs for those materials will be discounted to the EIO-LCA base year. Currently, the base year is 1997.

Scenario Information: The user can define up to 5 water sources or analysis scenarios in this table. For example, the utility may want to compare alternative water sources such as surface water, groundwater, recycled water, desalinated water, and imported water. The user might instead want to compare different scenarios for the same water source, e.g., obtaining groundwater from three different aquifers. The user might want to compare different alternatives for a particular treatment process, such as chlorination, chloramination, ozone, or UV disinfection.

System Information:

- WATER SYSTEM NAME: Defines the utility to be analyzed.
- SYSTEM LOCATION: Allows the user to select the state where the utility is located from a drop-down menu. This is a required input.
- WATER SYSTEM ACRONYM: Allows the user to define a shortened form of the utility name which may be used elsewhere in the tool. This is an optional input.

Service area and Customer demographics: Allows the user to input information about the service area and customer break-down of the utility. Information in these categories is optional.

Water Source Information:

- WATER SYSTEM NAME: Defines the utility to be analyzed.
- SYSTEM LOCATION: Allows the user to select the state where the utility is located from a drop-down menu. This is a required input.
- WATER SYSTEM ACRONYM: The user can enter a shortened version of their utility name to be used elsewhere in the tool. Entry is optional.

Facility Information: The facility table allows user to define the infrastructure that processes water in the system. It can include different sections of pipeline or aqueduct, different treatment plants, or different sections of the distribution system. A new facility should be defined for any infrastructure that processes a different water phase, source, or water or a significantly different volume of water. The following are columns in the facility table.

- FACILITY NAME: The user can define a name for each facility. The name can be general or specific. For example, for an aqueduct system which supplies water to the system, the name can be general (Water supply) or specific (East Aqueduct). These facility names are used in the drop-down menus on later data entry pages.
- OWNED BY: The user can indicate whether the infrastructure is owned by their own utility or another entity (e.g., a water wholesaler). The default entry is the water system acronym defined above. Entry into this column is optional.
- WATER SYSTEM PHASE: User selects the water system phase (supply, treatment, or distribution) from the drop-down menu.
- WATER SOURCES %: User defines the percentage from each user-defined water source or scenario is processed through each facility. Often, the entry is 100% and may include 100% of multiple scenarios. A few examples:
    - If data is entered on the potable distribution system, all scenarios that create potable water will be entered at 100% (e.g., desalination, groundwater, imported, surface water).
    - If there are multiple treatment plants in the system that treat water from the same source(s), enter the percentage of water from each source that are processed through the plant.
- ANNUAL PRODUCTION: Enter the volume of water produced in a particular year or an average year for each of the facilities defined. This number will be used to normalize the results to the defined functional unit.

7.1.2. Material Production and Delivery

Figure 4 shows another example data entry page. The user enters data about materials used in construction, operation, and maintenance as well as information about material delivery.

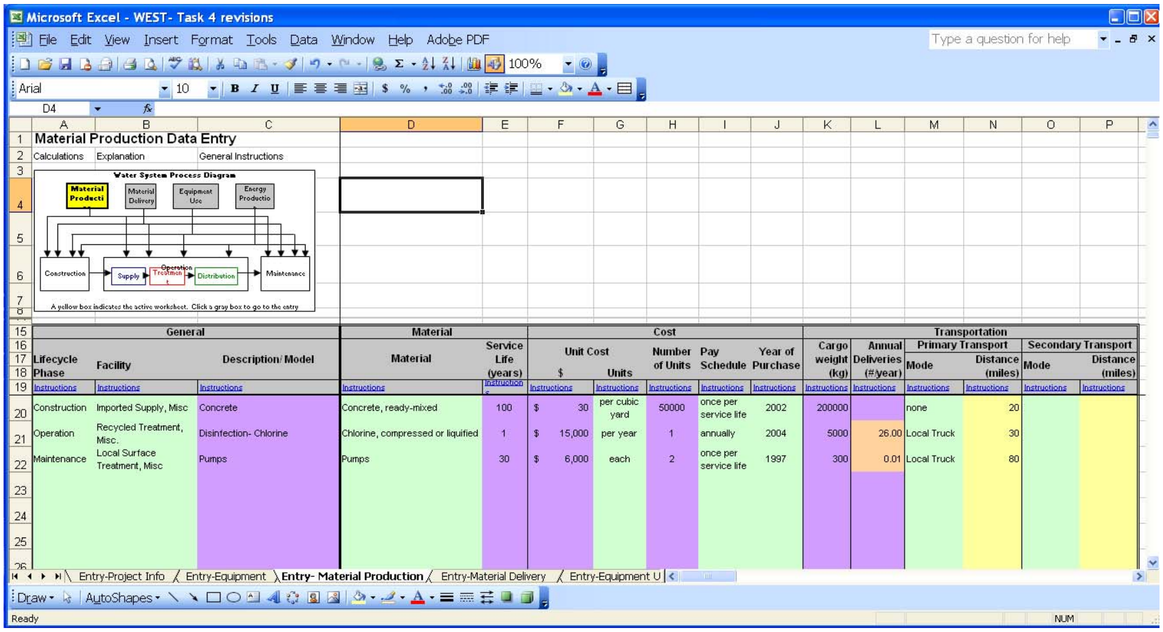


Figure 4: ***Entry- Material Production*** **Worksheet**

The following describes data entry for the Material Production activity:

- LIFECYCLE PHASE: The user should select the appropriate life-cycle phase construction, operation, and maintenance) from the drop-down menu for each material. Life-cycle phases are defined in Table 1.
- FACILITY: Select the appropriate facility where the material is used. Facilities are defined by the user on the Project Info sheet. This information is used to correctly allocate the material to the desired source or scenario and to normalize the result based on water production at the facility.
- DESCRIPTION/MODEL: The user may opt to enter additional description here for reference. It is not necessary for calculations.
- MATERIAL: Select a material from the drop-down menu. A list of materials included in WEST as well as default service lives and delivery distances are shown in Table 1. Custom materials can be added to WEST if the user has LCA inventory data for energy use and emissions.
- SERVICE LIFE: A value will be automatically entered for the selected material from the default values shown in Table 1. The service life for the material can be edited by the user.
- DATA TO BE ENTERED: A values will be automatically filled in based on the material selection. This provides guidance for the user on what to enter in the next cell for unit cost (or weight). If the material's EFs are based on EIO-LCA, the user should enter a cost value. If the EFs are from a process-based source, the user should enter weight in kg. Table 1 indicates which EF source is used for all materials.
- UNIT COST (or weight): The user should enter the cost or weight associated with each material entered. The user can enter total cost or cost per length, weight, or other unit. If you enter a

cost, the value will be discounted to 1997 dollars for the calculations so enter the value in terms of dollars from a single year (i.e., do not discount future purchases). If purchases for a material are to be made in multiple years, you can enter each purchase in separate lines for each purchase or discount all purchases to a single year and enter it once.

- UNITS: Select the most appropriate unit from the drop down menu (total, per length, per weight, per volume, per piece, per year).
- NUMBER OF UNITS: Enter the number of units for the cost value entered. For example, it the cost you entered is $10 per kg, enter the number of kg used. If you entered the total value for the system, enter 1.
- PAY SCHEDULE: Select the appropriate pay schedule from the drop-down menu. The choices are: one time, once per service life, or annually. If you have entered a cost/weight that will only be used once in analysis period, select one time. If you have entered a cost/weight for single purchase of a material that will be replaced over the analysis period (i.e., filter materials, pumps), enter once per service life. If the material is consumable and will be purchased every year, enter annually.
- YEAR OF PURCHASE: Enter the year associated with the cost entered for Unit Cost, if applicable. If the unit cost is in 2008 dollars, enter 2008.

The final columns on this page allow data entry for the Material Delivery calculations, including:

- CARGO WEIGHT: Enter the estimated weight of the material in kg.
- ANNUAL DELIVERIES: Value is automatically calculated based on the pay schedule selection and the service life.

The user can enter data on two serial modes of transportation (for example, a train offloaded to a local truck). For primary transport and, if applicable, secondary transport, the user should enter:

- MODE: User should select the appropriate mode of transportation from the drop-down menu (local truck, long-distance truck, train, ship, or plane).
- DISTANCE: Value is automatically entered based on the default values shown in Table 1. It can be edited by the user.

7.1.3. Equipment Use

Two entry pages or present for defining equipment use, one defines the equipment itself and the other defines the amount and purpose of equipment use. The first is the *Entry-Equipment* page, a portion of which is shown in Figure 5. This worksheet defines the characteristics of equipment used by the system. Custom equipment can be entered at the bottom of the worksheet. The page also shows characteristics for material delivery equipment.

WEST 031810 [Compatibility Mode]

EQUIPMENT DATA

Instructions

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

Select equipment models from drop-down menu.

Equipment Details

Row	Activity	Equipment	Brand/Model	Engine Capacity (hp)	Productivity		Vehicle Type	Fuel Consumption		Fuel Type	Emissions Category
15	Concrete Placement	Concrete Mix Truck	International 5500i	565	41		Road	0.1	gal/mile	diesel	DR
16		Concrete Pump	Schwing BPL1200	476			Non-road	25	gal/hr	diesel	NR300TO600
17		Concrete Vibrator	Oztec 1.8 oz				Electric	1800	watts	electric	Electric
18		Rebar Cutter	Diamond DC-32X				Electric	1200	watts	electric	Electric
19		Rebar Bender	Multiquip MB-25				Electric	1200	watts	electric	Electric
20	Excavation and Earthwork	Large Excavator	Caterpillar 375	428			Non-road	24.72	gal/hr	diesel	NR300TO600
21		Small Excavator	John Deere 200C	141			Non-road	9.731	gal/hr	diesel	NR100TO175
22		Backhoe Loader	Caterpillar 420D	88			Non-road	6.693	gal/hr	diesel	NR50TO100
23		Vibratory soil compactor	Ingersoll-Rand SD100D	125			Non-road	32.65	gal/hr	diesel	NR100TO175
24		Grader	Caterpillar 140H NA	165			Non-road	10.92	gal/hr	diesel	NR100TO175
25		Dozer with ripper	Caterpillar D8N	285			Non-road	18.87	gal/hr	diesel	NR175TO300
26		Wheel loader	John Deere 644E	160	4		Non-road	10.59	gal/hr	diesel	NR100TO175
27		Dump Truck	GMC c8500	275	22		Road	0.077	gal/mile	diesel	DR
28	Concrete Paving	Slipform paver	Wirtgen SP 250	105.8981233			Non-road	5.205	gal/hr	diesel	NR100TO175
29		Texture curing machine	Wirtgen TCM 850	47			Non-road	2.272	gal/hr	diesel	NR25TO50
30	Asphalt Paving	Paver	Cedarapids CR451	172			Non-road	11.39	gal/hr	diesel	NR100TO175
31		Pneumatic roller	Dynapac CP221	100			Non-road	6.62	gal/hr	diesel	NR100TO175
32		Tandem roller	Ingersol rand DD110	125			Non-road	8.627	gal/hr	diesel	NR100TO175
33	Meter Reading and Maintenance	Pickup Truck	Average Truck	NA	NA		Road	13	gal/mile	Other1	GR
34		Automobile	Average Car	NA	NA		Road	30	gal/mile	Other2	GR
35	Sludge Removal	Dump Truck (sludge)	Sterling L8500	250	22	ton/tri	Road	0.077	gal/mile	diesel	DR
36		Wheel loader (sludge)	John Deere 624E	135	360	ton/h	Non-road	9.317	gal/hr	diesel	NR100TO175

Entry- Material Production | Entry-Equipment | Entry-Equipment Use | Entry-Ener

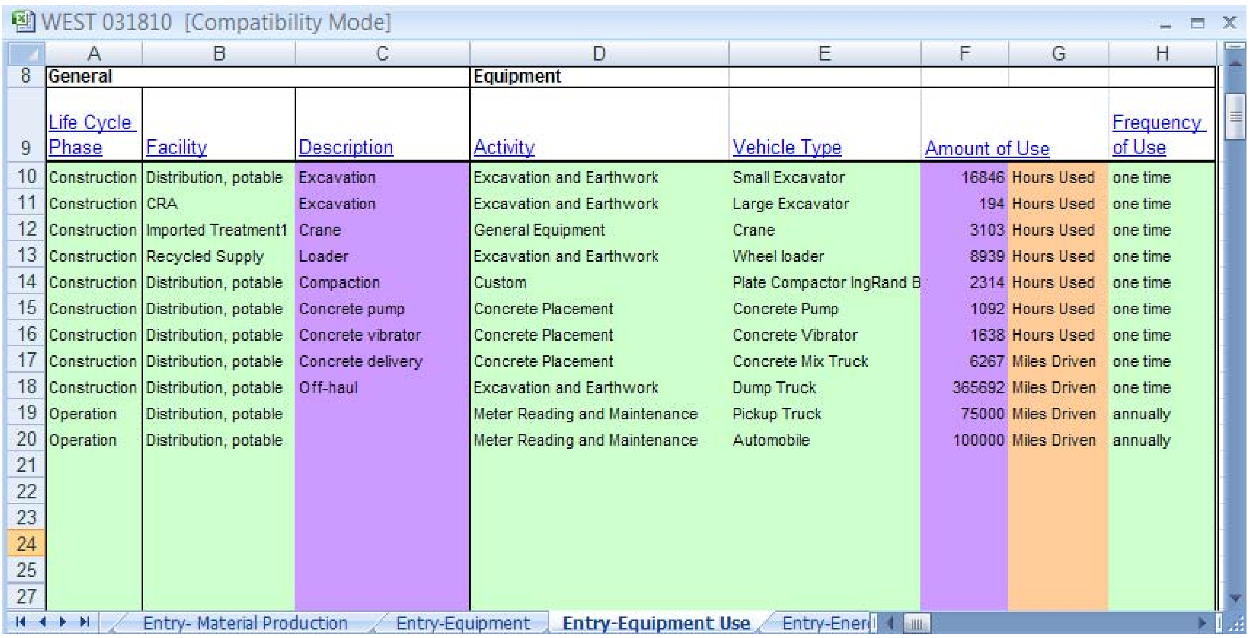
Figure 5: *Entry-Equipment* Worksheet

The following data can be entered by the user, though all information on this sheet has default values assigned and edits are optional:

- BRAND/MODEL: For each equipment type, the user can select a model from a drop-down menu or enter customized data. Custom equipment categories can also be entered at the bottom of the worksheet.
- ENGINE CAPACITY: A default value in units of horsepower will be updated based on the model selection. The user can edit as needed.
- PRODUCTIVITY: A default value in the units indicated will be updated based on the model selection. The user can edit as needed.
- VEHICLE TYPE: The vehicle type (road or non-road) will be automatically entered.
- FUEL CONSUMPTION: A default value in units of gallons per mile for road equipment and gallons per hour for non-road equipment will be updated based on the model selection. The user can edit as needed.

- FUEL TYPE: The user can select the fuel type from the drop-down menu among gasoline, diesel, electric, and two customizable fuels. The EFs for the fuels are defined on the *Entry-Energy Mix* worksheet.
- EMISSIONS CATEGORY: The category is entered automatically based on prior inputs and should not be edited.

The second data entry page is the *Entry- Equipment* use worksheet, shown in Figure 6, is used to enter the amount of equipment use needed for the system.


WEST 031810 [Compatibility Mode]

	A	B	C	D	E	F	G	H
8	General			Equipment				
9	Life Cycle Phase	Facility	Description	Activity	Vehicle Type	Amount of Use		Frequency of Use
10	Construction	Distribution, potable	Excavation	Excavation and Earthwork	Small Excavator	16846	Hours Used	one time
11	Construction	CRA	Excavation	Excavation and Earthwork	Large Excavator	194	Hours Used	one time
12	Construction	Imported Treatment1	Crane	General Equipment	Crane	3103	Hours Used	one time
13	Construction	Recycled Supply	Loader	Excavation and Earthwork	Wheel loader	8939	Hours Used	one time
14	Construction	Distribution, potable	Compaction	Custom	Plate Compactor IngRand B	2314	Hours Used	one time
15	Construction	Distribution, potable	Concrete pump	Concrete Placement	Concrete Pump	1092	Hours Used	one time
16	Construction	Distribution, potable	Concrete vibrator	Concrete Placement	Concrete Vibrator	1638	Hours Used	one time
17	Construction	Distribution, potable	Concrete delivery	Concrete Placement	Concrete Mix Truck	6267	Miles Driven	one time
18	Construction	Distribution, potable	Off-haul	Excavation and Earthwork	Dump Truck	365692	Miles Driven	one time
19	Operation	Distribution, potable		Meter Reading and Maintenance	Pickup Truck	75000	Miles Driven	annually
20	Operation	Distribution, potable		Meter Reading and Maintenance	Automobile	100000	Miles Driven	annually
21								
22								
23								
24								
25								
27								

Entry- Material Production | Entry-Equipment | **Entry-Equipment Use** | Entry-Ener

Figure 6: *Entry-Equipment Use* Worksheet

The following data is to be entered on this worksheet:

- LIFECYCLE PHASE: The user should select the appropriate life-cycle phase construction, operation, and maintenance) from the drop-down menu for each material. Life-cycle phases are defined in Table 1.
- FACILITY: Select the appropriate facility where the material is used. Facilities are defined by the user on the Project Info sheet. This information is used to correctly allocate the material to the desired source or scenario and to normalize the result based on water production at the facility.
- DESCRIPTION: The user may opt to enter additional description here for reference. It is not necessary for calculations.
- CATEGORY: The user should collect the equipment category from the drop-down menu. The categories are defined on the *Entry-Equipment* worksheet and categorize the types of equipment. The categories choices and associated equipment are as follows:

Category	Equipment Types
Concrete Placement	Concrete mix truck, Concrete pump, Concrete vibrator, Rebar cutter, Rebar bender
Excavation & Earthwork	Large excavator, Small excavator, Backhoe loader, Vibratory soil compactor, Grader, Dozer with ripper, Wheel loader, Dump truck
Concrete Paving	Slipform paver, texture Curing Machine
Asphalt Paving	Paver, Pneumatic roller, Tandem roller
Meter Reading & Maintenance	Pickup Truck, Automobile
Sludge Removal	Dump truck (sludge), Wheel loader (sludge)
General Equipment	Generator, Air compressor, Crane, Cutting torch, Forklift, Power saw, Welder, Tanker truck, Pedestal boom

Table 3: Equipment Categories

The user can also enter custom equipment on the Entry-Equipment worksheet.

- VEHICLE TYPE: Select the specific type of equipment from the drop-down menu. The list is populated based on the category choice made in the previous column.
- AMOUNT OF USE: Enter the amount of use for the equipment and facility indicated. The units, either hours used or miles driven, will be automatically populated based on the type of equipment chosen. When the equipment is primarily for on-road use, the miles driven should be entered. When the equipment is for off-road use, the hours used should be entered.
- FREQUENCY OF USE: The user should select whether the amount of use occurs once (e.g., during initial construction) or annually (e.g., for maintenance).

7.1.4. Energy Production

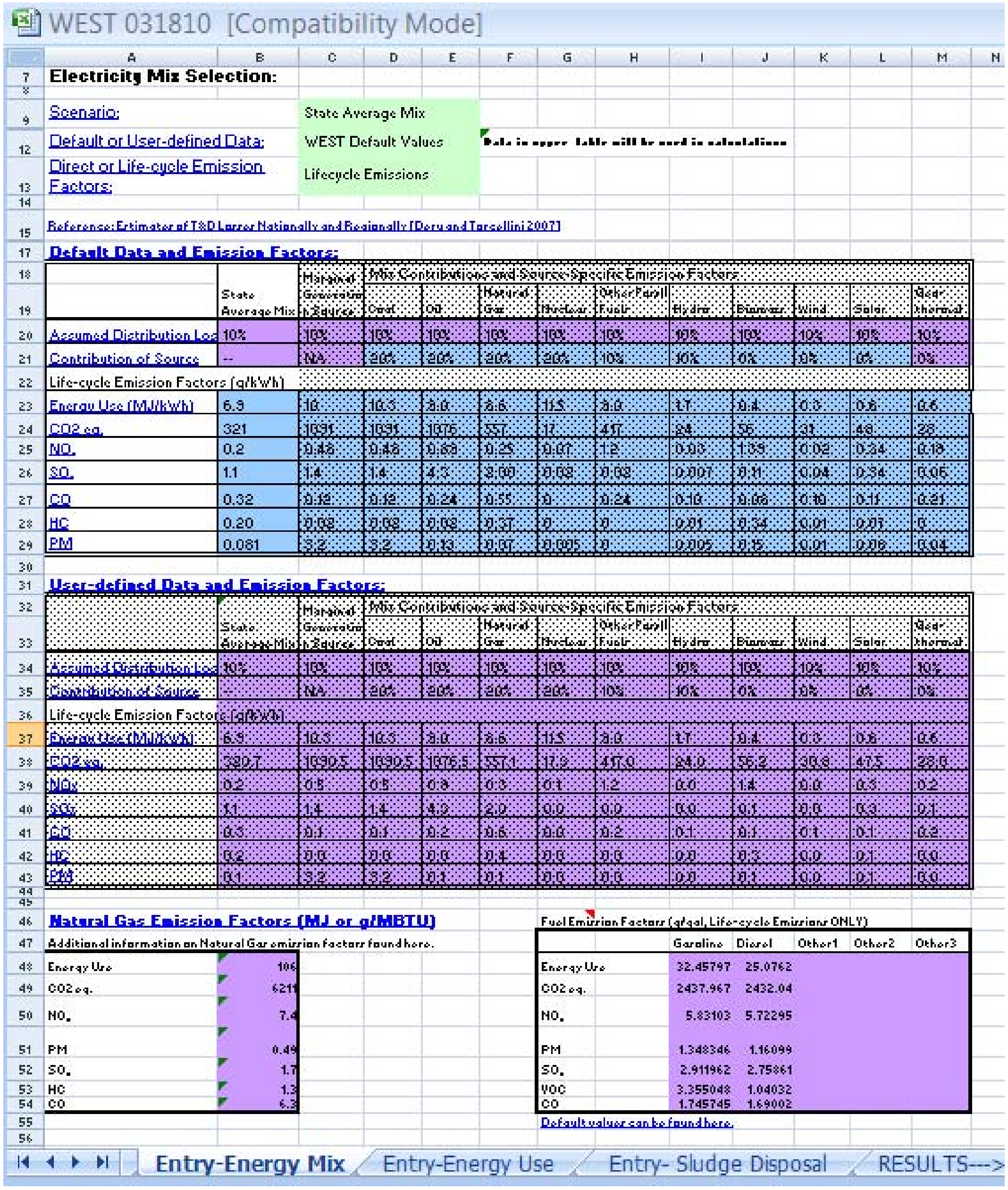
Two entry worksheets are present for the energy production activity. The first, *Entry-Energy Mix,* is used to enter information about the electricity mix and also to edit EFs for natural gas combustion and fuel production. The second, *Entry, Energy Use,* is used to enter the amount of electricity and natural gas consumption needed to operate the system. Figure 7 shows the *Entry-Energy Mix* worksheet.

Defaults are present for all the inputs of this page. Edits are optional. The following describes the inputs on this page:

Electricity Mix Selection:

- SCENARIO: Select the desired electricity mix from the drop-down menu. The choices are: State average mix, National average mix, and Custom generation mix. The default value is State-average Mix which is selected based on the location entered on the *Entry-Project Info* worksheet.
- DEFAULT OR USER-DEFINED DATA: Select whether the user wishes to use the default EFs or define their own. The default selection is to use the default data.

- DIRECT OR LIFECYCLE EMISSION FACTORS: Select whether to use EFs for direct (i.e., smokestack) or life-cycle (i.e., including supply chain) emissions. The default value is lifecycle emissions.



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Electricity Mix Selection:

Scenario:	State 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:

	State Average Mix	Marginal Generation Source	Coal	Oil	Natural Gas	Nuclear	Other Fossil Fuels	Hydro	Biomass	Wind	Solar	Geothermal
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)	6.9	10	10.3	3.0	8.6	11.5	3.0	1.7	0.4	0.3	0.6	0.6
CO_2 eq.	321	1091	1091	1076	557	17	417	24	56	31	48	28
NO_x	0.2	0.48	0.48	0.69	0.25	0.07	1.2	0.03	1.39	0.02	0.34	0.18
SO_x	1.1	1.4	1.4	4.3	2.00	0.02	0.02	0.007	0.11	0.04	0.34	0.05
CO	0.32	0.12	0.12	0.24	0.55	0	0.24	0.10	0.06	0.10	0.11	0.21
HC	0.20	0.02	0.02	0.02	0.37	0	0	0.01	0.34	0.01	0.01	0
PM	0.081	3.2	3.2	0.13	0.07	0.005	0	0.005	0.15	0.01	0.06	0.04

User-defined Data and Emission Factors:

	State Average Mix	Marginal Generation Source	Coal	Oil	Natural Gas	Nuclear	Other Fossil Fuels	Hydro	Biomass	Wind	Solar	Geothermal
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)	6.9	10.3	10.3	3.0	8.6	11.5	3.0	1.7	0.4	0.3	0.6	0.6
CO_2 eq.	320.7	1090.5	1090.5	1076.5	557.1	17.2	417.0	24.0	55.2	30.8	47.5	28.0
NO_x	0.2	0.5	0.5	0.9	0.3	0.1	1.2	0.0	1.4	0.0	0.3	0.2
SO_x	1.1	1.4	1.4	4.2	2.0	0.0	0.0	0.0	0.1	0.0	0.3	0.1
CO	0.3	0.1	0.1	0.2	0.6	0.0	0.2	0.1	0.1	0.1	0.1	0.2
HC	0.2	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.3	0.0	0.1	0.0
PM	0.1	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
CO_2 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			
CO_2 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.

Entry-Energy Mix / Entry-Energy Use / Entry- Sludge Disposal / RESULTS--->

Figure 7: ***Entry-Energy Mix*** **Worksheet**

Default or User-Defined Data and Emission Factors.

Based on the selections made, cells in these tables which are relevant to the calculations will be left clear while others are grayed out.

- ASSUMED DISTRIBUTION LOSS: The user can edit the assumed transmission and distribution losses. The default value is 10%. A hyperlink to reference information on electricity system losses is present above the table, if needed.
- CONTRIBUTION OF SOURCE: When a customized generation mix is selected, the user should enter the percentage contribution from each source. If the values sum to less than 1, the remainder of the electricity is assumed to come from the state-average mix.

The remainder of the table is composed of default EFs for each possible electricity source. In the default values table, the values are provided for reference only. They can be edited in the lower table.

Natural Gas and Fuel Emission Factors. These tables provide default data for direct combustion of natural gas as well as production of fuels such as gasoline and diesel that will be used in vehicles and equipment. The user can enter other fuels as desired. Additional EFs for fuels (e.g., biodiesel, ethanol, fuel cells) can be found on the Fuel EFs worksheet in the background information

Figure 8 shows *the Entry-Energy Use* worksheet which is used to enter information on electricity and natural gas consumption for each facility. The following describes entry into this worksheet:

- LIFECYCLE PHASE: The user should select the appropriate life-cycle phase construction, operation, and maintenance) from the drop-down menu for each material. Life-cycle phases are defined in Table 1.
- FACILITY: Select the appropriate facility where the energy is used. Facilities are defined by the user on the Project Info sheet. This information is used to correctly allocate the material to the desired source or scenario and to normalize the result based on water production at the facility.
- DESCRIPTION: The user may opt to enter additional description here for reference. It is not necessary for calculations.

For both natural gas and electricity, enter:

- AMOUNT: Enter the number of kWh of electricity used and/or the number of therms of natural gas consumed.
- FREQUENCY: Select the frequency of use (per year or per AF) for the amount of electricity or natural gas previously entered.
- TOTAL kWh/THERMS USED: Calculates the annual consumption of electricity or natural gas based on previous entry.

Fuel Use Table

The table shows calculated amounts of fuels used to operate equipment as defined on the *Entry-Equipment Use* worksheet. These cells should not be edited by the user.

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ELECTRICITY USE

			Electricity Use			Natural Gas use		
Lifecycle Phase	**Facility**	**Description/ Model**	**Amount**	**Frequency**	**Total kWh Used**	**Amount (therms)**	**Frequency**	**Total therms**
Operation	Recycled Supply		0	per year			per year	
Operation	Recycled Treatment		50000	per year	50000		per year	
Operation	Recycled Distribution		30000	per year	30000		per year	
							0	
							0	
							0	
							0	
							0	
							0	
							0	
							0	
							0	
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							0	
							0	

FUEL USE- Equipment Use (gal)

Fuel consumption information is calculated in the Calcs-Equipment Use worksheet (click to go to sheet).

	Construction										
	Supply			Treatment			Distribution			Supply	
Fuel Consumption	I	D	R	I	D	R	I	D	R	I	D
Gasoline	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	7.E-02	0.E+00	0.E+00	0.E+00	####
Diesel	5.E-03	0.E+00	0.E+00	7.E-01	0.E+00	0.E+00	2.E+01	0.E+00	0.E+00	0.E+00	####
Electricity	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	4.E-01	0.E+00	0.E+00	0.E+00	####

Entry-Energy Mix | **Entry-Energy Use** | Entry- Sludge Disposal | RESULTS--->

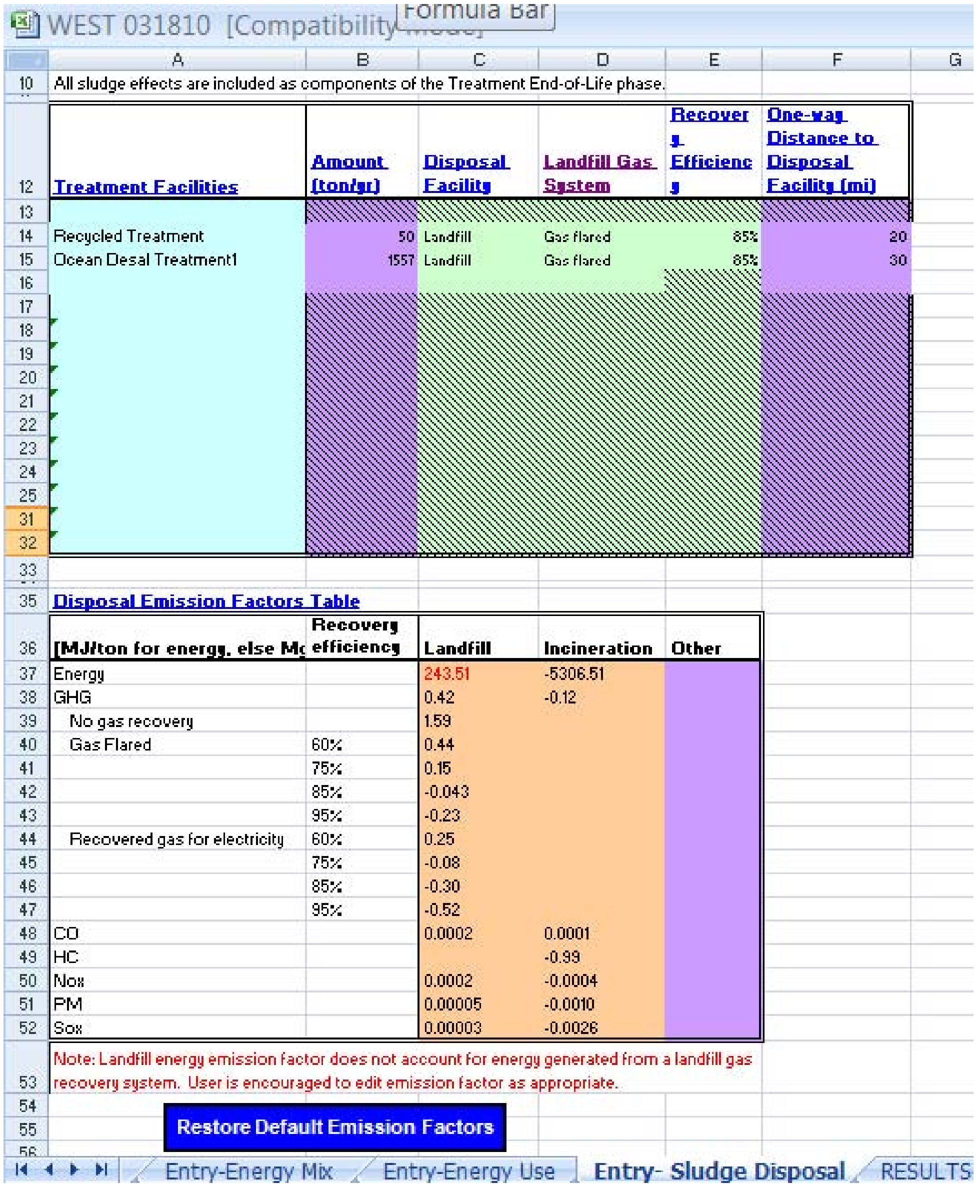
Figure 8: *Entry-Energy Use* Worksheet

7.1.5. Sludge Disposal

Figure 9 shows the entry worksheet for the sludge disposal activity. Descriptions of the needed inputs are provided. All sludge disposal emissions are automatically assigned to the end-of-life phase.

- TREATMENT FACILITY: Select the appropriate treatment facility from the drop-down menu. There may be gaps in the list so scroll down if the desired facility is not shown.
- AMOUNT: Enter the amount of sludge produced from sedimentation in units of tons/year (1 ton – 2000 lb).
- DISPOSAL FACILITY: Select landfill, incineration, or other from the drop-down menu.
- LANDFILL GAS SYSTEM: Select the appropriate option for landfill gas capture (no capture, gas flared, gas used for electricity).
- RECOVERY EFFICIENCY: If applicable, select the efficiency of the recovery system.

- DISTANCE: Enter the one-way distance to the disposal facility in miles.



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All sludge effects are included as components of the Treatment End-of-Life phase.

Treatment Facilities	Amount (ton/yr)	Disposal Facility	Landfill Gas System	Recovery Efficiency	One-way Distance to Disposal Facility (mi)
Recycled Treatment	50	Landfill	Gas flared	85%	20
Ocean Desal Treatment1	1557	Landfill	Gas flared	85%	30

Disposal Emission Factors Table

[MJ/ton for energy, else Mg	Recovery efficiency	Landfill	Incineration	Other
Energy		243.51	-5306.51	
GHG		0.42	-0.12	
No gas recovery		1.59		
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%	-0.30		
	95%	-0.52		
CO		0.0002	0.0001	
HC			-0.99	
Nox		0.0002	-0.0004	
PM		0.00005	-0.0010	
Sox		0.00003	-0.0026	

Note: Landfill energy emission factor does not account for energy generated from a landfill gas recovery system. User is encouraged to edit emission factor as appropriate.

Restore Default Emission Factors

Entry-Energy Mix | Entry-Energy Use | Entry- Sludge Disposal | RESULTS

Figure 9: Entry-Sludge Disposal Worksheet

Disposal Emission Factors Table If desired, edit the EFs associated with landfill disposal, incineration, or a custom disposal alternative in units of MJ or Mg per ton.

7.2. Results Worksheets

Several results worksheets are available. Results are reported in terms of functional unit (i.e., per volume of water treated) and are shown numerically and graphically on each sheet. Results are given for each defined water source as defined on the Project Information entry page. Results are also given for the cumulative water system. Results for each source are distributed proportionally based on their contribution to the overall water production.

A summary page, seen in Figure 10, provides total results for all activities. Results pages for each separate activity are also available with a similar format. The user can customize results pages to show additional results as desired.

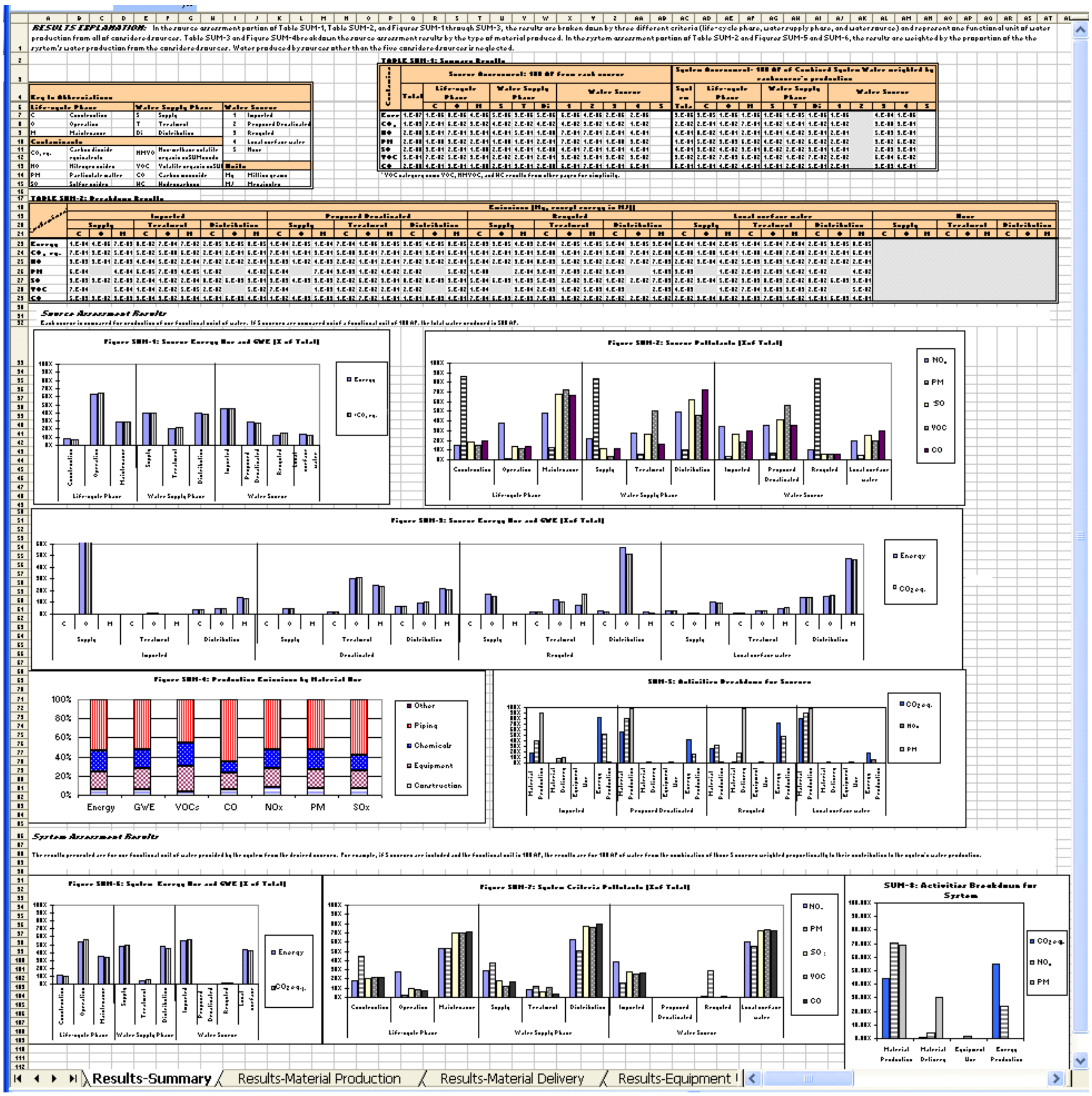

Figure 10: Summary Results

7.3. Calculations Worksheets

Calculation worksheets are present for each of the five activities described in the Entry section. These worksheets are locked so that users can not inadvertently change an equation.

7.4. Explanatory Worksheets

Hyperlinks are present throughout the tool that link to explanations of the cell contents and equations used. These worksheets provide similar content as this user manual but are more detailed. The explanatory (EXP) worksheets include:

- Exp- Revisions: Provides a list of revisions made to the WEST tool since it's original release.
- Exp- Project Info
- Exp-Material Production
- Exp-Material Delivery
- Exp-Energy Production
- Exp-Sludge Disposal

7.5. Data Worksheets

Background worksheets are present with data necessary to complete the LCA calculations. These worksheets are locked so that users can not inadvertently change data. The following are the names and brief descriptions of the data worksheets:

- Definitions (Defs): includes the list and default assumptions about material choices, ENR's Construction Cost Index data for discounting, and terms for certain drop-down mists.
- Final air EFs: Summarizes EFs for air emissions from EIO-LCA and other sources.
- Final water EFs: Lists EFs for water emissions.
- EMF transport: Includes EFs for diesel trucks.
- External (Ext) costs: Provides cost estimates for various air emissions which can be used to provide a single number estimate for air emissions in terms of dollars. The value range widely and are highly uncertain so caution should used when applying them to the results.
- Conversions: Includes unit conversions, material densities, heat contents, global warming potentials of GHGs, and similar data.
- Other Transport Data: Lists EFs for delivery and transport vehicles such as automobiles and light trucks.
- CARB MSC99-32: Contains general performance and emissions data for off-road construction and maintenance equipment.
- Equipment pool: Provides specific performance data for commonly used construction equipment.
- Equipment use impacts: Contains EFs for some non-road diesel and gasoline equipment and direct electricity EFs.
- Disposal: Lists EFs for disposal options.
- EGRID EFs: Provides estimates of direct fuel-specific electricity EFs

- Elect LC EFs: Summarizes life-cycle EFs for specific fuels and state-by-state estimates as well as a literature summary of electricity LCAs.
- Fuel EFs: Describes EFs for fuel production for a variety of fuels including gasoline, diesel, ethanol, biodiesel, and fuel cells.

8.0 Where else can I learn about WEST?

Additional information on this research can be found in the following publications:

- Stokes, J. Life-cycle Assessment of Alternative Water Supply Systems in California. Unpublished Ph.D. dissertation. University of California, Berkeley, California. May 2004.
- Stokes, J. and A. Horvath. "Life Cycle Energy Assessment of Alternative Water Supply Sources," International Journal of Life Cycle Assessment, (5) 335-346. 2006.
- Stokes, J. R. and A. Horvath (2009). "Energy and Air Emission Effects of Water Supply." Environmental Science & Technology **43**(8): 2680-2687.

In addition, reports were made to the funding agency, the California Energy Commission, which contain detailed information on the work completed. The final report for the initial phase of work (completed 2003-2004) is located at:

http://www.energy.ca.gov/pier/final_project_reports/CEC-500-2005-101.html

The final report for the work completed between 2006 and 2010 should be available on the Energy Commission website in early 2011.

9.0 Acknowledgments

Funding for WEST has been provided by the California Energy Commission Public-Interest Energy Research (PIER) program.

10.0 Frequently Asked Questions (FAQs)

How can I obtain the tool and learn about changes to the tool and the user's guide?

WEST users should request a copy of the tool and companion documentation by registering with the tool authors by sending an email to UCBWaterLCA at gmail dot com with following information:

- Name
- Email
- Phone and fax number
- Employer, school, or other affiliation
- The tool you are interesting in (WEST, WESTCalc, WWEST)
- Purpose for using the tool

Registered users will be notified of updates to the tool and to the user's manual when they become available. Both the tool and the documentation will be updated as project constraints allow.

I do not agree with default assumptions present in WEST or WESTCalc. How can I suggest changes?

Most assumptions in WEST can be changed by the user in the tool. In some cases, a cell may need to be unlocked prior to the change.

In addition, the tool creators are always interested in improving WEST by including better default assumptions about, for example, material service lives, delivery distances, equipment and material costs, and EFs. Please send your suggestions to the tool developers at UCBWaterLCA at gmail dot com so they can be included in future tool versions.

How can I change the values in a locked cell?

On data entry and results pages, the password needed to unlock cells is "WEST." A different password is used for calculation and background pages. The tool developers do not encourage changes to these pages. If the user wishes to change cells on these worksheets, please contact the tool developers at UCBWaterLCA at gmail dot com to obtain the password.

I am getting an error message in the results (#REF or #NAME, etc,). What can I do to resolve this?

First, a tip: DO NOT SORT data that has been entered in the tool OR DELETE lines out of the entry tables. This will cause errors in the calculations.

If that does not resolve the problem, review the activity specific results (i.e., Results- MP, Results- EP) pages to see which calculations are causing the error. If the error is occurring in many cells on all pages, the error is likely to be related to the basic data entry on the Entry-General Info page. A required entry may have been left blank in the Facilities table, for example. If the omission is not obvious, follow the instructions for more specific errors.

If only one cell or a few cells are showing error messages,go to the corresponding Calcs page and try to identify which input is causing the error. Scroll down through the calcs to find where it is occurring. When it is located, highlight a cell with the error message. If you highlight portions of the formula and hit F9 you can identify what the value is being assigned to each term in the formula.

11.0 References

California Air Resources Board. (2002). "Off-Road Emissions Model." Retrieved May 1, 2002, 2002, from http://www.arb.ca.gov/msei/msei.html.

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Appendix A.1.2:
WEST Revision Logs

Summary of Revisions to WEST

Revised: 3/18/2010

Prior CEC Task

Date	Description of Change
6/10/2010	- corrected formatting and protection errors on the Entry pages - corrected calculation errors for Energy on Calcs-MD; for CO2 & Energy calcs for GR & DR vehicles on Calcs-EU; for fuel use air emissions on Calcs-EP; & for fuel calcs on Calcs-SD
3/18/2010	- created internal and external versions of WEST and WWEST for limited release
3/15/2010	-Updated equipment pool to consolidate fuel consumption for gas, diesel, and electric; simplified units for fuel consumption; updated equipment entry page.
3/12/2010	- Inserted new emission factors for fuel production from GREET model (2010)
3/1/2010	- Updated electricity life-cycle emission factors so that they are as specific as possible to Western climate and most common fuel sources (i.e., PV park solar and large reservoir-based hydropower)
1/20/2010	- Inserted new EGRID emissions factors from State 2005 worksheet
1/10/2010	-Corrected certain equipment use calculations that were not adjusted by functional unit correctly
12/1/2009	- Added improved passenger transport emission factors (Chester 2008) to the "Other transport data" worksheet that can be used to analyze commuting or other non-freight applications
11/5/2009	- Edited emission factors for freight transport (material delivery) with data from Facanha and Horvath 2007, simplified aircraft Efs, and deleted aircraft data page
7/31/2009	- added additional air & water data; corrected calculations so Gabi data to properly tabulated
6/27/2007	- Revised the "Energy Mix" entry page to properly reference the national average life-cycle emission factors - Completed "Exp-Energy Production" and "Exp-Sludge Disposal" sheets
6/18/2007	- Changed life-cycle electricity emission factors for each of the 50 states to use the state-specific emission factors for each source rather than the national averages.
6/14/2007	- Edited "Entry-Sludge Disposal" worksheet to include a macro to reset emission factors
6/13/2007	- Completed checking calculations for sludge disposal - Created "Results- Sludge Disposal" worksheet and edited "Results-Summary" page to include an end-of-life phase
6/12/2007	- Finalized sludge disposal entry page.
6/11/2007	- Added electricity transmission and delivery loss estimates nationally and for regions of the grid to the "EGRID Efs" worksheet for reference by the user - Updated the data in the "Elect LC Efs" worksheet to include Deru and Torcellini data and to correct some mathematical errors
5/29/2007	- Updated the Facility Table to include sludge production data on the "Entry-Project Info" worksheet
5/24/2007	-Removed PM and VOC emission factors for direct emissions on the "Equipment Use Impacts" worksheet because they are based on a life-cycle study
5/23/2007	- Updated WEST with E-GRID 2007 data, including marginal emission factors for each state in "Egrid EFs" worksheet - Revised the electricity emision factors in the "Euipment Use impacts" worksheet - Added Life-cycle emission factors to WEST in the "Elect LC EFs" worksheet
4/19/2007	- Added emission factors to WEST for PM and NMVOCs by state and nationally
4/16/2007	- Revised the equation for the "Current Year" on the Project Information worksheet; it had not been updating properly and was reading '2006'

4/3/2007	- Added data from Engineering News Record's Construction Cost Index for years 2003-2005
4/2/2007	- Added drop-down menu for Year of Purchase on the Material Production worksheet from years that CCI data is available - Resaved file as WEST- Task 4 revisions
3/9/2007	- Revised the list of material options for Material production to include some customizable cells which can be edited by a user as need and still show up on the drop-down menu.
2/7/2007	- Revised Material Production Allocation factors for Maintenance and Construction to removed double counting of maintenance effects.
1/12/2007	- Removed the "% to Water System term from the explanatory pages of the file; still need to remove it from the "Entry Project Info" page and the calculations
1/7/2006	- Revised explanation worksheets to reflect changes caused by allowing customized input of up to 5 water sources. Changes did not affect equations. Textual changes were made to the Exp-Project Info worksheet and to the allocation factors section of the pages for the Exp-Material Production, Exp-Material Delivery, Exp-Equipment Use, and Exp-Energy Production worksheets. - Rearranged Project Info worksheet to place Model and Source Information tables on the left and the System Information table on the right. This structure is more intuitive for the user because data entered into Source Information table affects headings in the System Information table and should therefore be entered first. - Edited Exp-Project Info worksheet to include documentation on the System Information table and fix hyperlinks on Project Info related pages to link correctly.
1/3/2007	- Completed calculation checks using Oceanside data based on state average emission factors - Confirmed that all equations still function properly using the Custom Generation Mix - Created a new file: water lca tool 010307
1/2/2007	- Cell reference errors were corrected on the Calcs-Material Production and Calcs-Material Delivery worksheets
12/20/2006	- Corrected definition of Water Sources percentages in the Facility Table. Previously, the percentage showed the percentage of water at the facility from each source. This causes a mis-allocation of materials when the facility was shared between two souces (most commonly for the potable distribution). For each functional unit of water processed, the emissions should be the same, regardless of source. This factor should be used instead to allocated results if only a percentage of water from a single source is processed through a facility. The Water Source percentage was inconsistently used in prior iterations of WEST.
12/19/2006	- Began checking tool using previously analyzed data from Oceanside system - Corrected allocation factors to allow additional material purchases when service life is less than analysis period and allocate the purchases to the Maintenance phase
12/13/2006	- Completed changes to results summary sheets
12/12/2006	- Created figures to show percentages of results for Material Production Results worksheet - Completed Energy Production calculation revisions - Created Material Delivery Results, Equipment Use Results, and Energy Production Results worksheet
12/11/2006	- Included a definition of direct emissions and life-cycle emissions on the Energy Production Explanation page. - Created a new file dated 121106 - Edited Material Production Results tables to accurately reflect the new setup of results data - Restructured material Production Results to report data in both absolute numbers and percentages - Created table to show results for both 100 AF of each source and for the weighted combination of water in the system
12/8/2006	- Completed Equipment Use calculation revisions in 120406 file
12/7/2006	- Completed Material Delivery Calc revisions
12/6/2006	- Completed Material Production Calc revisions
12/5/2006	- Corrected errors in calculations on material production page caused by copying over data

12/4/2006	- Begin revisions of tool for Energy Commission Task 3: Assess Alternative Water Supply Sources; dated 120406 - Edited Project Info worksheet to allow additional/custom water sources and edited the Project Info explanation worksheet to reflect change
12/1/2006	- Updated Energy Production Calc explanation to include distribution loss in the equation
11/30/2006	- Added this journal of summary of revisions and updated with work from the last month. - Created new file dated 113006
11/27/2006	- Corrected certain equations after comparing results using this version of WEST to result from a prior version.
11/21/2006	- Corrected energy calculations so when the Custom Generation Mix does not equal 1, the remainder of electricity is assumed to use the state-average emission factors. - On the E-GRID EFs worksheet, the CO_2 emission factor for 'Other fossil fuels' corrected; a cell was referenced wrong before.
11/1/2006	- Completed calculations of emission factors for each of the nine possible electricity sources based on interpolation of E-GRID Year 2000 Plant data. For each plant, the electricity was classified as being from one of the nine sources based on information in the E-GRID documentation. For each source, the national average emission factor was calculated. In addition, for each state, emission factors were calculated for each electricity source produced in that state. For electricity produced from municipal solid wastes, 30% of the emissions were allocated to the other fossil fuel sources and 70% to biomass, as specified in the E-GRID documentation. The calculations were done in a separate file and final values were added to WEST as the EGRID EFs worksheet. - The "Energy Mix" worksheet was updated to read in the calculated emission factors. The state-specific emission factor is used when a source is generated within the state. The national-average emission factor is used otherwise.
10/31/2006	-Updated Energy Calculations worksheet to correctly reference the emission factor cells depending on the users choices from drop-down menus on the "Energy Mix" data entry page.
10/25/2006	- Created separate "Energy Mix" and "Energy Use" data entry worksheets. Moved the Default data table created on 10/18/06 and the user-defined entry table created 10/25/06 to this page. - Created a Scenario drop down menu so user can select whether to use State Average Mix, Custom Generation Mix, or Marginal Generation Source. - Created drop-down menu so user can select whether to use WEST default values or User-defined values. - Created a drop-down menu so user can select whether to use Direct Emissions or Lifecycle emissions. The additon of Lifecycle emission data is part of Task 5 of this project but the menu was added now as a place-holder to minimize future work.
10/24/2006	- Added a table to the Energy Production worksheet to allow for User-defined Emission Factor entry.
10/20/2006	- Allocated the Marriott and Matthews category 'Other' proportionately across the other electricity sources defined by E-GRID (other fossil fuels, nuclear, solar, wind, geothermal). - Determined the percentage of the 'other' sources were attributable to each of the 5 sources for each state and allocated the emissions accordingly. - Calculations were not completed. Since this work is out-of-scope for the task, WEST was edited to allow the use of this data in the future, but it was not incorporated at this time.
10/19/2006	- Entered State-Specific Electricity Consumption Data on Electricity Data 00 worksheet. Source: Marriott and Matthews 2005, "Environmental Effects of Interstate Power Trading on Electricity Consumption Mixes"' Environmental Science and Technology, 39(22),8584-8590. Tables from Supporting Information for all 50 States. - The Marriott and Matthews data includes five categories: Coal, Oil, Gas, Hydro, and Other.
10/18/2006	- Checked E-GRID website for updated data but was not available. A revision was expected in September 2006. Sent and email to EPA to receive a notice when the next revision is available. - Added a table to the Energy Production worksheet so the emission factors to be used in calculations are shown on data entry page.

Appendix A.1.3:
WEST Help Pages

Project Information Data Entry Instructions

PURPOSE: This worksheet allows the user to specify information on the water system and its facilities and model parameters.

Data Entry Worksheet

Color convention

Purple	Columns or cells where data should be entered by user
Green	Columns or cells that include drop down menus to be filled in by user
Yellow	Columns or cells where assumptions made should be checked by user
Orange	Columns or cells containing calculations
Pink	Columns containing data entered elsewhere in the spreadsheet
Blue	Columns or cells that include data from other sources and should be verified by user

Hyperlinks in left columns link to column described.

Model Information Table

Analysis Period	Enter the analysis period (years). The analysis period should approximately equal the expected service life of the most-durable of the system facilities so that emissions are allocated correctly.
Current Year	The cell calculates the current year. Edit the cell if the year is incorrect.
Functional Unit	Enter the desired functional unit in AFA. The functional unit should be large enough to allow comparison of results.
EIOLCA Base Year	Enter the year which is used in the EIOLCA model. The default value is 1997. This should not change until updated EIO information has been incorporated into the EIOLCA model.

Source Information Table

Source	User should enter the names of the water sources to be considered. Up to five sources can be entered. If desired, the user can consider particular facilities or other components of the system besides water sources.

System Information Table

Water System Name		Enter the name of the water system being analyzed.
System Location		Select the state where the system is located from the drop-down menu. The state is used to determine the appropriate electricity emissions factors to use.
Water System Acronym		Enter a short name for the water system (max: 6 letters) which \will be used to identify the system elsewhere in the spreadsheet
Service Area Demo-graphi	**Population**	Enter the population served by the water system being analyzed.
	Area	Enter the area served by the water system in square miles.
Customer Demographics		Enter the percentage of customers that are classified as residential, industrial, commercial, institutional, irrigation, and other customers. Residential custormers should be further broken down into single-family and multi-family residences. This data is for informational purposes only and is not used in the analysis.
Water Sources		Enter the volume of water produced in acre-feet annually (AFA) for each to be included in the analysis (maximum: 5 sources). The percentage of water produced from each source will be calcuated automatically. Make sure that the percentage for the total water produced (top right corner of this section of the table) is 100% to ensure proper accounting of water.

Facility Information Table

Name	Enter the facility name, if desired. Several default values are provided (e.g., imported supply, non-potable distribution). These can be used if the default values for water source percentage and percent water to system are applicable for the facility. Facilities should be added if the default values are not applicable or if it makes tracking data inoput more transparent.
Owned By	This value is for informational purposes only. The cell default value is the Water System Acronym defined above.
Water System Phase	Select the appropriate water phase classification (supply, treatment, or distribution) for the facility. Refer to the diagram at the top of the page if it is unclear how a facility should be classified in the system.
Water Source	Enter the percentage of water from the specified water source which is processed at the facility. This does not mean to enter the percentage of water in the facility which is from the source. For example, if the distribution system is used for all potable water of which 35% is imported and 65% is local groundwater, the percentage entered for both imported and local groundwater is 100%.
Production	Enter the volume of water processed at the facility in AFA.

Equipment Data Entry Instructions

PURPOSE: This worksheet allows to select the equipment used in constructing, operating, and maintaing the water system. Data entered on this worksheet is used to calculate emissions due to material delivery, equipment use, and fuel production.

Color convention

- (purple) Columns or cells where data should be entered by user
- (green) Columns or cells that include drop down menus to be filled in by user
- (yellow) Columns or cells where assumptions made should be checked by user
- (orange) Columns or cells containing calculations
- (pink) Columns containing data entered elsewhere in the spreadsheet
- (blue) Columns or cells that include data from other sources and should be verified by user

Hyperlinks in left columns link to column described.

Equipment Details

Activity	This column identifies common activities in the life-cycle of a water system. They are defined as a guide and may not apply to all uses of the equipment. Custom equipment (i.e., equipment not listed in the table already) should be added in the final category by editing the appropriate line on the *Equipment Pool* worksheet.
Equipment	This column contains a list of equipment which would be commonly used in each of the defined activites. Custom equipment may be added as described above.
Brand/Model	Select the desired brand and/or model from the drop-down menu. The list in the menu is defined on the *Equipment Pool* worksheet and is catagroized by the equipment type. If the model desired is not listed, find the correct section of the *Equipment Pool* worksheet and edit the line marked 'Custom' or select the closest substitute.
Engine Capacity, Power, Productivity, Fuel Consumption, Fuel Type, and Emissions Category	The values for each of these parameters depend on the brand and model chosen in Column C. The parameters are defined on the *Equipment Pool* worksheet. The sources for all the equipment data are listed in Column of the *Equipment Pool* table. Values which are assumed will have comments attached to them which say that.

Diesel Road Equipment Assumptions

Model Year	Select the appropriate model year from the drop-down menu. Model year lists are based on choices in the "Diesel Emissions for On-Road Eqpuipment" table on the *Equipment Use Impacts* worksheet.
Cumulative Miles	Enter the approximate milage on the average vehicle. Mileage can change the emissions rate for some pollutants.

Diesel Non-Road Equipment Assumptions

Model Year	Select the appropriate model year from the drop-down menu. Model year lists are based on choices in the "Diesel-Powered Non-Road Equipment" table on the *Equipment Use Impacts* worksheet.

Material Production Data Entry Instructions

PURPOSE: This worksheet allows the user to enter materials used in the construction, operation, and maintenance phases of the facilities in their water supply system. Information entered is used to determine the environmental burden caused by material production (i.e., emission at the manufacturing plant and in the supply chain) and delivery (i.e., emissions from trucks, trains, barges, and planes used to transport the materials to the site).

Color convention

Purple	Columns or cells where data should be entered by user
Green	Columns or cells that include drop down menus to be filled in by user
Yellow	Columns or cells where assumptions made should be checked by user
Orange	Columns or cells containing calculations
Pink	Columns containing data entered elsewhere in the spreadsheet
Blue	Columns or cells that include data from other sources and should be verified by user

Hyperlinks in left columns link to column described.

General	Life-cycle Phase	Select the appropriate life-cycle phase (construction, operation, and maintenance) from the drop-down menu.
	Facility	Select the facility where material will be used from the drop-down menu. The facility must be entered in the Facility Information table in the 'Entry-Project Info' worksheet to appear in the list.
	Description /Model	Enter a description of the material if desired.
Material	Material	Select the material from drop-down list (if material is not available, please select closest substitute or contact tool developer). Drop-down list is defined in the first column of the EIO Sectors table on the 'Defs' worksheet. Any material added to the EIO Sectors table MUST be associated with an EIO Sector. Information on these sectors is available on the EIOLCA website (see source list).
	Service life	Enter the service life of the material (i.e., the average time before replacement is expected). Service life should be entered in years.
Cost	Unit Cost	Please enter the cost per unit of the material (in $) in the first column and select the appropriate units from the dropdown menu in the second column. If the desired units are not listed, select 'Other' or add the desired units to the Units table in the 'Defs' worksheet. Unit costs for some material may be available in the 'Costs' worksheet. Cost information is used to estimate environmental burden due to material production. Calculations used in this estmiation are described below.
	Number of Units	Enter the number of units purchased at the listed unit cost. If the number of units is expected to vary over the analysis period, either enter an average value or group the volumes into larger bundles (e.g., enter the total units for 5 years). If units are bundled into larger units, the pay schedule should be entered as 'once per service life" and the service life should be the number of years in the bundle. Each bundle should be listed as a separate line item.
	Pay schedule	Select the appropriate pay schedule from the drop-down menu (one-time, once per service life, or annually). Please make sure the pay schedule and number of units are consistent. For instance, if the chosen pay schedule is annually, please enter the number of units purchased each year.
	Year of Purchase	Enter the year of purchase or the year the unit cost is reported in (i.e., 2002 if the cost is in 2002 dollars). This value will be used to discount the costs to the EIOLCA base year. Discounting is described in more detail below.
Transport	Cargo weight	Enter the weight of the material to be transported. This value is used to calculate emissions from the truck, airplane, barge, and/or train used to deliver the materials to the site.
	Annual Deliveries	The annual deliveries value estimates the number of trips per year. For materials that are only purchased once, or are purchased once during their surface life, this value is calculated automatically based on the service life and/or the analysis period. For materials purchased annually, the user should enter the average number of deliveries to the site (i.e., a certain volume of chlorine may be purchased annually, but deliveries are made 7 times a year).
	Transport Mode	Select the primary and ,if needed, secondary mode of transport (truck, train, barge, or airplane) from the drop- down menu. This information is used to calculate emissions associated with transporting materials to the site.
	Transport Distance	Enter the distance, in miles, that the material will be transported using the associated transport mode.

DISCOUNTING TIPS:

This model simply discounts the cost as described in the calculations below. This calculation only adjusts the costs for inflation and does not account for other changes in price. If the user desires a more refined analysis, please do one of the following:

- Enter in the average price for the material over the entire analysis period. This value should be discounted to a base year which should be entered in the "Year of Purchase" column.
- Group the purchases into bundles of one year or more where price is relatively stable and enter the average price for that period. The price should be discounted to a single base year which will be entered in the "Year of Purchase." If units are bundled into units larger than one year, the pay schedule should be entered as 'once per service life" and the service life should be the number of years in the bundle. Each bundle should be listed as a separate line item.

Material Production Calculations

Hyperlinks in left columns link to column described.

General		Information in this catagory is obtained from the 'Entry-Material Production' worksheet.
Material		Information in this catagory is obtained from the 'Entry-Material Production' worksheet.
Cost	**Unit Cost**	Information in this catagory is obtained from the 'Entry-Material Production' worksheet.
	Number of Units	Information in this catagory is obtained from the 'Entry-Material Production' worksheet.
	Pay Schedule	Information in this catagory is obtained from the 'Entry-Material Production' worksheet.
	Year of Purchase	Information in this catagory is obtained from the 'Entry-Material Production' worksheet.
	Lifecycle Cost (LCC)	If Pay Schedule = One time, then LCC is calculated as follows: $$LCC = UnitCost * NumberofUnits$$ Unit Cost and Number of Units are obtained from Columns E and G of this worksheet. If Pay Schedule = Annually, then LCC is calculated as follows: $$LCC = UnitCost * NumberofUnits * AnalysisPeriod$$ Unit Cost and Number of Units are obtained from Columns E and G of this worksheet. Analysis Period is found on the 'Entry-Project Info' worksheet in the Model Information Table. If Pay Schedule = Once per Service Life, then LCC is calculated as follows: $$LCC = UnitCost * NumberofUnits * AnalysisPeriod / ServiceLife$$ Unit Cost and Number of Units are obtained from Columns E and G of this worksheet. Analysis Period and Service Life are found on the 'Entry-Project Info' worksheet in the Model Information Table.
	EIO LCC	LCC results are discounted to obtain comparable values useful in the EIOLCA model (default is 1997). The calculation uses Engineering News Record's Construction Cost Index (CCI) and is as follows: $$EIOLCC = LLC * \frac{1997CCI}{YearofPurchaseCCI}$$ Year of Purchase is obtained from Column I of this worksheet, LCC is calculated in Column J of this worksheet. CCI information is found in the CCI table on the Defs worksheet.
	Functional Unit Cost	Functional Unit Cost compares all costs for the same volume of water production and is calculated as follows: $$FunctionalUnitCost = EIOLCC * FunctUnit / AnalysisPeriod \ / \ Annual\,Production$$ EIOLCC is calculated in Column K of this worksheet. Functional Unit and Analysis Periond are obtained from the Model Information table on the 'Entry-Project Info' worksheet. Annual Production is from the Facility Information table on the 'Entry-Project Info' worksheet. These values are specific to the facility listed in Column B of this worksheet. % Water to System will be less that 100% if the facility provides water to multiple water systems.
EIO Sector		EIO Sector is assigned based on the Material listed in Column C of the worksheet. Assignments are listed in the EIO Sectors Table on the 'Defs' worksheet [Source: EIOLCA 2003].
Environmental Burden per Functional Unit		Emission (or use for energy) for each category are calculated according to the following equation: $$Emissions = EIOLCAEmissionFactor * FunctionalUnitCost$$ EIOLCA Emission Factors (EFs) are reported in Mg per dollar spent in the sector (or MJ/$ for energy) on the 'EIOLCA EFs' worksheet [Source: EIOLCA 2003]. These factors are specific to each EIO Sector and emission category. Functional Unit Cost was calculated in Column L of this worksheet.
Allocation Factors		Allocation factors are determined by: the life-cycle phase (Column A), the water supply phase, and proportion of water processed at the relevant facility. The latter two are associated with the facility (Column B) in the Facility Information Table on the 'Entry-Project Info' worksheet. Allocation factors range from 0 to 1 and are fractional when the water is processed from multiple sources is processed at the facility.

Sources:

EIOLCA 2003 — Carnegie Mellon University Green Design Initiative. (2003) Economic Input-Output Life Cycle Assessment (EIO-LCA) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 6 Nov, 2003]

All ofher data is provided by the user.

Material Delivery Data Entry Instructions

PURPOSE: This worksheet allows the user to view transportation data for materials used in the construction, operation, and maintenance phases of the facilities in their water supply system. The data is originally entered into the "Entry-Material Production" worksheet and should be edited there. This information entered is used to determine the environmental burden caused by delivering the necessary materials to the construction site. Material delivery by truck, train, ship, and airplane are considered.

Color convention

- Columns or cells where data should be entered by user
- Columns or cells that include drop down menus to be filled in by user
- Columns or cells where assumptions made should be checked by user
- Columns or cells containing calculations
- Columns containing data entered elsewhere in the spreadsheet
- Columns or cells that include data from other sources and should be verified by user

Hyperlinks in left columns link to column described.

General	Life-cycle Phase	Information in this column is obtained from the 'Entry-Material Production' worksheet.
	Facility	Information in this column is obtained from the 'Entry-Material Production' worksheet.
	Description/Model	Information in this column is obtained from the 'Entry-Material Production' worksheet.
Transportation	Transport Mode	Information in this column is obtained from the 'Entry-Material Production' worksheet.
	Transport Distance	Information in this column is obtained from the 'Entry-Material Production' worksheet.
	Cargo weight	Information in this column is obtained from the 'Entry-Material Production' worksheet.
	Annual Deliveries	Information in this column is obtained from the 'Entry-Material Production' worksheet.

Material Delivery Calculations

umns link to column described.

General		Information in this category is obtained from the 'Entry-Material Production' worksheet.
Transportation	Primary Mode	Information in this category is obtained from the 'Entry-Material Production' worksheet.
	Primary Distance	Information in this category is obtained from the 'Entry-Material Production' worksheet.
	Secondary Mode	Information in this category is obtained from the 'Entry-Material Production' worksheet.
	Secondary Distance	Information in this category is obtained from the 'Entry-Material Production' worksheet.
	Annual Deliveries	Information in this category is obtained from the 'Entry-Material Production' worksheet.
	Cargo weight	Information in this category is obtained from the 'Entry-Material Production' worksheet.
	Functional Unit Adjustment	The functional unit adjustment is calculated as follows: $FUA = AnnualDeliveries / AnnualProduction * FunctionalUnit$ where Annual Deliveries is displayed in Column P, Annual Production is the amount of water produced at the facility in question (AF/yr) and is obtained from the Facility Table on the "Entry-Project Info" worksheet, and Functional Unit is obtained from the Model Information Table in the "Entry-Project Info" worksheet.
Emissions	**General**	In general, emissions are calculated as follows: $Emissions_{ij} = (\sum_{j=1}^{2} Emissions_{ij}) * FUA$ Where *I* is the pollutant and *j* is the transport mode being evaluated. Specific emission calculations for pollutants and transport modes are described below.
	GWE	GWE is calculated as follows for all modes of transportation: $GWE = \sum_{m=1}^{n} GWP_m * Emissions_m$ Where GWP for each greenhouse gas *m* is found in the 'Global Warming Potential' table on the *Conversions* worksheet. GWP for CO2 is equal to 1. Emissions for each greehmouse gas *m* are calculated in Columns AA-AC.
	Other modes:	The following calculations are used to determine emissions, except for GWE: $Emission_{ij} = EmissionFactor_{ij} * CargoWeight * Distance$ Where *I* is the pollutant and *j* is the transport mode being evaluated. Emission factors are found in the Cargoemissions table on the "Other Transport Data" worksheet. Cargo weight and distance are in listed in previous columns.
Allocation Factors		Allocation factors are determined by: the life-cycle phase (Column A), the water supply phase, and proportion of water processed at the relevant facility. The latter two are associated with the facility (Column B) in the Facility Information Table on the 'Entry-Project Info' worksheet. Allocation factors range from 0 to 1 and will be fractional when the water is processed at multiple facilities.
Transport Miles Traveled Per Functional Unit		Miles traveled by primary or secondary transport mode are determined as follows: $Miles_j = AF * Distance_j * FUA$ where j is the primary or secondary transport mode and AF, Distance, and FUA are all reported in previous columns.
Diesel Fuel Used per FU		Diesel fuel use (gallons) is calculated for all relevant transport as follows $DieselUse = \sum_{j=1}^{2} Miles_j * CargoWeight * FuelEfficiency_j$ where j is the primary or secondary transport mode and Fuel Efficiency (gal/kg/mile) is from the Cargo Emissions table in the "Other Transport Data" worksheet. Cargo Weight is provided in an earlier column.

Energy Table

Energy Used	The energy used in each phase is estimated by the following equation: $$EnergyUsed_k = FuelUsed_k * EnergyContent_k / 1000000$$	
	Where k is either jet or diesel fuel, energy content found on the 'Conversions' worksheet and equals 1.36×10^8 J/gal and 1.42×10^8 J/gal, respectively; fuel used is reported in gallons in a previous column. Results are reported in megajoules; the factor of 1,000,000 converts J to MJ.	

Summary Table

Energy	Cells in this table sum the energy used in burning jet and diesel fuel as reported in the energy table for the appropriate phase. Results are reported in MJ.
PM, SO_2. CO, HC, NO_x, N_20, CH_4, CO_2, GWE NMVOC, VOC	These columns sum the products of the appropriate allocation factor and the emissions of the pollutant considered and divide by 1,000,000 to convert from grams to Mg.

Fuel Use Table

Fuel Used	Reports fuel used to transport materials in gallons by summing the values in the diesel and jet fuel used columns described above.

Sources:

EIOLCA Carnegie Mellon University Green Design Initiative. (2003)
Economic Input-Output Life Cycle Assessment (EIO-LCA) model [Internet],
Available from: <http://www.eiolca.net/> [Accessed 6 Nov, 2003]

All ofher data is provided by the user.

Equipment Use Data Entry Instructions

PURPOSE: This worksheet allows the user to enter equipment use data used in the construction, operation, and maintenance phases of the facilities in their water supply system.

Color convention

Purple	Columns or cells where data should be entered by user
Green	Columns or cells that include drop down menus to be filled in by user
Yellow	Columns or cells where assumptions made should be checked by user
Orange	Columns or cells containing calculations
Pink	Columns containing data entered elsewhere in the spreadsheet
Blue	Columns or cells that include data from other sources and should be verified by user

Hyperlinks in left columns link to column described.

General	Life-cycle Phase	Select the appropriate life-cycle phase (construction, operation, and maintenance) from the drop-down menu.
	Facility	Select the facility from the drop-down menu; facilities are defined in the Facilities Table on the "Entry-Project Info" worksheet.
	Description	Enter a description of the equipment or its use, if desired.
Equipment	Activity	Select the activity for which the equipment is used from the drop-down menu; activities and associated equipment are assigned in the table on the "Equipment" worksheet. The activity is associated with a code which is hidden in Column E.
	Vehicle Type	Select the vehicle type from the drop-down menu; the list of vehicles in the drop-down menus depends on the activity selected in the previous column and is defined on the "Equipment" worksheet.
	Amount of Use	Enter the amount the vehicle is used; units will be in either "Miles Driven" or "Hours Used" and will be determined automatically (in Column I) depending on vehicle type chosen in the previous column.
	Frequency of Use	Select the frequency of use from the drop-down menu (annual or one-time) and make sure the selection corresponds to the amount of use provided in Column H.

Equipment Use Calculations

Hyperlinks in left columns link to column described.

General		Information in this category is obtained from the *Entry-Equipment Use* worksheet.
Equipment Information	Vehicle Type	Information in this category is obtained from the *Entry-Equipment Use* worksheet.
	-	Information in this category is obtained from the *Entry-Equipment Use* worksheet.
	Amount of Use	Information in this category is obtained from the *Entry-Equipment Use* worksheet.
	Use Frequency	Information in this category is obtained from the *Entry-Equipment Use* worksheet.
	Power Source	Information in this category is obtained from the *Entry-Equipment* worksheet and is based on the Vehicle Type listed in Column C.
	Engine Capacity	Information in this category is obtained from the *Entry-Equipment* worksheet and is based on the Vehicle Type listed in Column C.
	Fuel consumption	Information in this category is obtained from the *Entry-Equipment* worksheet and is based on the Vehicle Type listed in Column C.
	Emission Code	Information in this category is obtained from the *Entry-Equipment* worksheet and is based on the Vehicle Type listed in Column C. Emission codes are as follows: Diesel Road (DR), Gasoline Road (GR), Gasoline Non-Road (Gasoline), and Diesel Non-road (NR***, where **** corresponds to a range of horsepower measurements), and Electric (electric).
	Functional Unit Allocation	The functional unit allocation (FUA) is calculated as follows if the frequency of use selected is "one time": $FUA = \frac{FunctionalUnit}{AnnualProduction * TimeFrame}$ If frequency of use in Column X is 'annual", then the FUA is calculated as follows: $FUA = \frac{FunctionalUnit}{AnnualProduction}$ where Annual Production is the amount of water produced at the facility in question (AF/yr) and is obtained from the Facility Table on the "Entry-Project Info" worksheet, Functional Unit and Analysis Period are obtained from the Analysis Information Table on the "Entry-Project Info" worksheet.

Environmental Burden

Diesel Road (DR) Vehicles

Emissions depend on the type of equipment is use. If the emission code is "DR", energy use is calculated as follows:

$$EnergyUse = \frac{DieselHeat\,Content * AmountofUse}{1000000 * FuelConsumption} * FUA$$

Where diesel heat content is listed on the I worksheet in J/gal, the factor of 1,000,000 converts J to MJ; amount of use is specified in Column E; and fuel consumption is in the "Equipment Details" table on the *Entry-Equipment* worksheet. The FUA is calculated in Column L.

CO_2 emissions for DR vehicles are as follows:

$$Emission = \frac{WeightEmissionFactor * DieselDensity * AmountofUse}{FuelConsumption} * FUA$$

Where the Weight Emission Factor (g CO_2/g diesel) and Diesel Density are found in the "Diesel Properties" Table on the *Equipment Use Impacts* worksheet (g/gallon) [SOURCE: EPA 1996], Amount of Use is specified in Column E (miles), Fuel Consumption is found in the "Equipment Details" table in the *Entry- Equipment Use* worksheet (miles/gallon), and FUA is calculated in Column L.

For emission code "DR", emissions of HC, CO, and NOx are calcuated as follows:

$$Emission = (EmissionFactor + \frac{DeteriorationFactor * CumulativeMiles}{10,000}) * AmountofUse * FUA$$

Where the emissions factor (EF) and Deterioration Factor (DF) are from the "Diesel Emissions for On-Road Vehicles" table on the *Equipment Use Impacts* worksheet [Source: USEPA 1995], The EF and DF depend on the Model Year; Model Year and Cumulative Miles are defined in the "Diesel On-Road Equipment Assumptions" table on the *Entry-Equipment* worksheet. Amount of use is specified in Column E. FUA is calcualted in Column L. When DF is 0, the DR term is ignored in the calculation.

No estimates are available for PM and SOX emissions from Diesel Road vehicles.

Electric Equipment

Environmental burden for electric equipment for all categories (energy use, CO2, HC, CO, Nox, PM, and Sox) are calculated as follows:

$$Burden = \frac{EmissionorUseFactor * AmountofUse * Power}{1,000} * FUA$$

Where the Emission Factor (g/kWh) or Use Factor for energy (MJ/kWh) are found in the XXXX table on the *Equipment Use Impacts* worksheet. The Emission or Use factor depends on the state, which is specified in the "Site Information" table on the *Entry- Project Info* worksheet. Power (watts) is found in the "Equipment Details" table on the *Entry- Project Info* worksheet. The factor of 1,000 converts watts to KW. Amount of Use is specified in Column E and FUA in Column L.

Gasoline Road (GR) Vehicles

For gasoline-powered road vehicles (emission code: GR), energy use is calculated as follows:

$$EnergyUse = \frac{EnergyContentofGas * AmountofUse}{FuelConsumption * GasDensity} * FUA$$

Where the Energy Content of Gas (MJ/lb) and Gas Density (lb/gal) are listed on the *Conversions* worksheet [SOURCE: XXX, Simintec 2003]; Fuel Consumption (miles/gal) is found in the "Equipment Details" table on the *Equipment worksheet;* Amount of Use (miles) is provided in Column E; and FUA is calculated in Column L.

CO2 emissions for GR vehicles are calculated as:

$$Emission = \frac{EmissionFactor * AmountofUse}{FuelConsumption} * FUA$$

Where the Emission Factor (g CO2/gal) is found in the "Automobiles and Trucks" table on the *Other Transport Data* worksheet [SOURCE: Environmental Defence 2003] and depends on the type of vehicle chosen in the "Equipment Details" table on the *Entry-Equipment worksheet;* Fuel Consumption is also found in the "Equipment Details" table; Amount of Use is listed in Column E and FUA in Column L.

For other emissions (HC, CO, Nox, and PM), the following equation is used:

$$Emission = EmissionFactor * AmountofUse * FUA$$

Where the Emission Factor (g/mile) is given in the "Automobiles and Trucks" table in the *Other Transport Data* table [SOURCE: Environmental Defence 2003]; Amount of Use (miles) is given in Column E and FUA is calcualted in Column L.

No estimates are available for SOX emissions from Gasoline-pwered Road vehicles.

Diesel Non-Road (NR*) Equipment

Environmental burden for diesel non-road equipment for all categories (energy use, CO_2, HC, CO, NO_x, PM, and SO_x) are calculated as follows:

$$Burden = EmissionorUseFactor * AmountofUse * EngineCapacity * FUA$$

Where the Emission Factor (g/hp/hr) or Use Factor for energy (MJ/hp/hr) are found in the"Diesel-Powered Non-Road Equipment" table on the *Equipment Use Impacts* worksheet [SOURCE: EPA 1998]. The appropriate Emission or Use Factor depends on the Engine Capacity, which is listed in Column I. Amount of Use is specified in Column E; FUA is listed in Column L.

	Gasoline Non-Road Equipment	Environmental burden for gasoline-powered non-road equipment (emission code: gasoline) for all categories (energy use, CO_2, HC, CO, NO_x, PM, and SO_x) are calculated as follows: $Burden = EmissionorUseFactor * AmountofUse * EngineCapacity * FUA$ Where the Emission Factor (g/hp/hr) or Use Factor for energy (MJ/hp/hr) are found in the"Gasoline-Powered Non-Road Equipment" table on the *Equipment Use Impacts* worksheet [SOURCE: EPA 1996]. The appropriate Emission or Use Factor depends on the Engine Capacity (horsepower), which is listed in Column I. Amount of Use is specified in Column E (hours); FUA is listed in Column L.
Fuel Use	Gasoline	If the emissions code is GR, then gasoline use (gallons) is found using the following equation: $GasUse = \frac{AmountofUse}{FuelConsumption} * FUA$ Where Fuel Consumption (miles/ gal)is defined in the "Equipment Details" table on the *Entry-Equipment* worksheet; Amount of Use (miles) is found in Column E and FUA in Column L. If emissions code is Gasoline, then gasoline use in gallons is: $GasUse = \frac{BSFC * AmountofUse * EngineCapacity}{GasDensity} * FUA$ Where Brake-Specifc Fuel Consumption (BSFC; lb/hp/hr) is found in the "Gasoline-Powered Non-Road Equipment: table on the *Equipment Use Impacts* worksheet [SOURCE: XXX}; Gas Density (lb/gal) is found on the *Conversions* worksheet [SOURCE: XXX]; Amount of Use (hours) is found in Column E, EngineCapacity (horsepower) in Column I, and FUA in Column L.
	Diesel	If the emissions code is DR, then diesel use (gallons) is found using the following equation: $DieselUse = \frac{AmountofUse}{FuelConsumption} * FUA$ Where Fuel Consumption (miles/ gal)is defined in the "Equipment Details" table on the *Entry-Equipment* worksheet; Amount of Use (miles) is found in Column E and FUA in Column L. If emissions code is Gasoline, then gasoline use in gallons is: $DieselUse = \frac{BSFC * AmountofUse * EngineCapacity}{DieselDensity} * FUA$ Where Brake-Specifc Fuel Consumption (BSFC; lb/hp/hr) is found in the "Diesel-Powered Non-Road Equipment: table on the *Equipment Use Impacts* worksheet [SOURCE: XXX}; Diesel Density (lb/gal) is found on the *Conversions* worksheet [SOURCE: XXX]; Amount of Use (hours) is found in Column E, EngineCapacity (horsepower) in Column I, and FUA in Column L.
	Electricity	Electricity Use is calculated as follows: $ElectricityUse = \frac{Power * AmountofUse}{1{,}000} * FUA$ Where Power is specified in Column J, Amount of Use in Column E, and FUA in Column L.
Allocation Factors		Allocation factors are determined by: the life-cycle phase (Column A), the water supply phase, and proportion of water processed at the relevant facility. The latter two are associated with the facility (Column B) in the Facility Information Table on the 'Entry-Project Info' worksheet. Allocation factors range from 0 to 1 and will be fractional when the water is processed at multiple facilities.

SUMMARY TABLE	This table sums the products of emissions and the allocation factors for each line in the table.

FUEL AND ELECTRICITY USE	This table sums the products of fuel use and allocation factors for each line in the table.

Sources:

EIOLCA Carnegie Mellon University Green Design Initiative. (2003)
Economic Input-Output Life Cycle Assessment (EIO-LCA) model [Internet],
Available from: <http://www.eiolca.net/> [Accessed 6 Nov, 2003]

All ofher data is provided by the user.

Abbreviations:

Energy Production Data Entry Instructions

PURPOSE: This worksheet allows the user to electricity and fuel used in the construction, operation, and maintenance phases of the facilities in their water supply system. Information entered is used to determine the environmental burden caused by electricity and fuel production.

Color convention

- Columns or cells where data should be entered by user
- Columns or cells that include drop down menus to be filled in by user
- Columns or cells where assumptions made should be checked by user
- Columns or cells containing calculations
- Columns containing data entered elsewhere in the spreadsheet
- Columns or cells that include data from other sources and should be verified by user

Shading convention

- Columns or cells which are not currently available for selection. Will be activated when data and calculations are complete.
- Columns or cells which are not currently relevant for the energy and emission scenarios defined by the user.

ENERGY MIX

Scenario	Select the appropriate scenario for the desired energy mix from the drop-down menu. This is relevant only for electricity delivered to the water system itself for system or equipment operation; electricity for material production is unaffected. The choices include: 1) State Average Mix (based on EGRID data for the state selected on the 'Project Info' worksheet) 2) Marginal Generation Source (currently the default marginal source is coal; other sources will be available in the future) and 3) Custom Generation Mix (allows the user to define the percentage of energy obtained from each of nine potential sources)
Generation or Consumption Mix	**[CONSUMPTION MIX CURRENTLY NOT AVAILABLE]** Select from the drop-down menu to indicate whether the energy mix breakdowns desired is the mix of energy generated in the state (from EGRID data) or the mix of energy consumed in the state (from literature).
Marginal Source	**[MARGINAL SOURCE SELECTION NOT CURRENTLY AVAILABLE; emission factors for marginal source are assumed to be coal emission factors]** Select the appropriate emission factor for the marginal generation of electricity (coal, oil, natural gas, nuclear, hydropower, solar, etc.)
Default or User-defined values	Select from the drop-down menu to indicate whether the WEST default values (EGRID-based as shown in top emission factor table) or User-defined Values (as entered into bottom table) should be used in the calculations.
Direct or Life-cycle Emission Factors	Select the desired emission factors from the drop-down menu. Direct emission factors are based on eGRID data and are estimates of "smoke-stack" emissions. Life-cycle emission factors are estimates of "cradle-to-grave" emissions and were obtained from literature (e.g., Spath and Mann XX, XXXX).

Emission Factor Tables	Default	Data in this table will be used when the WEST Default Values option is selected. Emission factors in this table should not be changed. The user may edit the assumed distribution losses and, if the Custom Generation Mix is selected, may edit the percentage of electricity associated with each source. If the sum of the electricity sources does not equal one, the remaining electricity is assumed to be from the State Average Mix.
	User-defined	The user should edit this table when the User-defined Values option is selected. Default values are shown for reference.
Energy Mix Data	Assumed Distribution Loss	The assumed distribution loss accounts for the fact that electricity demand at the end-use is lower than the electricity that must be generated at the plant to meet the demand due to losses in the distribution system. The default value of 10% is based on the national average loss for electricity transmission and distribution [Deru and Torcellini 07]. Regional data from this source is available on the EGRID EFs worksheet. These values can be edited by the user.
	Contribution of Source	These values represent the breakdown of different electricity sources in the mix. When the Custom Generation Mix is selected, these can be edited to allow the user to evaluate any desired energy mix. If the sum of the electricity sources is less than one, the State Average Mix is used to make up the difference.
Default Emission Factors	Energy Use (MJ/kWh)	DIRECT: Default emission factor for all sources is 3.6, the conversion factor between megajoules and kilowatt-hours. LIFECYCLE: Default values arecalculated for the state, national average, and source-specific emission factors as described on the "LC Elect EFs" worksheet.
	CO2 eq, NOx, SOx (g/kWh)	DIRECT: Default emission factor for greenhouse gas emissions (in units of CO_2 equivalents), SO_x, and NO_x are obtained from EPA's EGRID database (Year 2000 data). The emission factor is equivalent to the state's average emission factor for the source or, if the source is not used in a particular state, the source's national average emission factor. LIFECYCLE: Default values ware calculated for the state, national average, and source-specific emission factors as described on the "LC Elect EFs" worksheet.
	CO (g/kWh)	DIRECT: Default emisson factor for all sources from Monterey County 21st Century General Plan Update Fact Sheet. See "Electricity Emissions" table on Equipment Use Impacts worksheet for more information. LIFECYCLE: Default values are calculated for the state, national average, and source-specific emission factors as described on the "LC Elect EFs" worksheet.
	HC, PM (g/kWh)	DIRECT: No default emission factors are provided because EPA's EGRID database does not estimate emissions for these emissions. LIFECYCLE: Default values are calculated for the state, national average, and source-specific emission factors as described on the "LC Elect EFs" worksheet.
User-defined Emission Factors	Energy Use (MJ/kWh)	DIRECT: Enter desired emission factor. Default emission factor for all sources is 3.6, the conversion factor between megajoules and kilowatt-hours. LIFECYCLE: Enter desired emission factor. Default values are calculated as described on the "LC Elect EFs" worksheet.
	CO2 eq, NOx, SOx (g/kWh)	DIRECT: Enter desired emission factor. Default emission factor for greenhouse gas emissions (in units of CO_2 equivalents), SO_x, and NO_x are obtained from EPA's EGRID database (Year 2000 data). The emission factor is equivalent to the state's average emission factor for the source or, if the source is not used in a particular state, the source's national average emission factor. LIFECYCLE: Enter desired emission factor. Default values are calculated as described on the "LC Elect EFs" worksheet.
	CO (g/kWh)	DIRECT: Enter desired emission factor. Default emisson factor for all sources from Monterey County 21st Century General Plan Update Fact Sheet. See "Electricity Emissions" table on Equipment Use Impacts worksheet for more information. LIFECYCLE: Enter desired emission factor. Default values are calculated as described on the "LC Elect EFs" worksheet.
	HC, PM (g/kWh)	DIRECT: Enter desired emission factor. No default emission factors are provided because EPA's EGRID database does not estimate emissions for these emissions. LIFECYCLE: Enter desired emission factor. Default values are calculated as described on the "LC Elect EFs" worksheet.

ENERGY USE

Electricity Use

Hyperlinks in left columns link to column described.

General	**Life-cycle Phase**	Select the appropriate life-cycle phase (construction, operation, and maintenance) from the drop-down menu.
	Facility	Select the facility where material will be used from the drop-down menu. The facility must be entered in the Facility Information table in the 'Entry-Project Info' worksheet to appear in the list.
	Description /Model	Enter a description of the material if desired.
Electricity Used	**Amount**	Enter the amount of electricity used (in kWh) in Column E.
	Frequency	Select the use frequency from the drop-down menu in Column F. It may be entered in terms of use per year or per acre-foot.
	Total kWh Used	The annual electricity use in kWh will be calculated automatically in Column G and should be reviewed by the user. The value will be equal to the value of Column E times the % water to system in the facilities table; if "per year" use is entered and for "per acre-foot" use will be calculated as follows: $AnnualElectUse = ElectUse * Annual\,Production * \%WatertoSystem$ Where ElectUse is specified in Column E, and Annual Production and % Water to System are associated with the specified facility and are found in the "Faciity Table" on the *Entry-Project Info* worksheet.

Fuel Use

Hyperlinks in left columns link to column described.

Material Delivery	This table summarizes diesel and jet duel used to deliver matrials to the system. Calculations for this table are found on the *Calcs-Material Delivery* spreadsheet and are displayed here for review by the user.
Equipment Use	This table summarizes gasoline, diesel and electricity used to operate equipment used in the system. Calculations for this table are found on the *Calcs-Equipment Use* spreadsheet and are displayed here for review by the user.

Energy Production Calculations

Electricity Production

Hyperlinks in left columns link to column described.

General		Information in this catagory is obtained from the *Entry-Energy Production* worksheet.
Electricity/ NG Use		Information in this catagory is obtained from the *Entry-Energy Production* worksheet.
Environmental Burden per FunctionalUnit	**Functional Unit Adjustment**	If Use Frequency is "per year", the functional unit adjustment (FUA) is as follows: $FUA = \frac{TotalkWh * FunctUnit}{Annual\,Production}$ If Use Frequency is "per acre-foot", the FUA is as follows: $FUA = TotalkWh * FunctUnit$ Where Total kWh is specified in Column F (therms for natural gas use throughout energy calcs), Functional Unit is defined in the 'Analysis Information' table; Annual Production is defined in the 'Facility Table'. Both tables are on the *Entry-Project Info* worksheet.
	Energy Use	Energy Use is calculated as follows: $Energy = \frac{UseFactor * TotalkWh * \sum_{sources}[(1 + DistributionLoss) * SourceContribution]}{FUA}$ Where the Use Factor is displayed on the Entry-Energy Mix worksheet. The state is specified in the 'System Information' table on the *Entry-Project Info* worksheet. Total kWh is specified in Column F, and the FUA is calcuated in Column G. The Distribution Loss and Source Contribution are defined on the Entry-Energy Mix worksheet.
	CO_2, NO_x, SO_2, and CO	Emissions of these pollutants are calculated by: $Emissions = \frac{EmissionFactor_i * TotalkWh * \sum_{sources}[(1 + DistributionLoss) * SourceContribution]}{1{,}000{,}000 * FUA}$ Where the Emission Factor for each pollutant *i* is displayed on the Entry-Energy Mix worksheet in the upper table if default values are selected and in the lower table if user-defined values are selected [SOURCE: EPA 2002, Monterey 2003, and DOE 1994]. The state is specified in the 'System Information' table on the *Entry-Project Info* worksheet. Total kWh is specified in Column F, and the FUA is calculated in Column G. The factor of one million converts grams to Mg. The Distribution Loss and Source Contribution are defined on the Entry-Energy Mix worksheet.
Allocation Factors		Allocation factors are determined by: the life-cycle phase (Column A), the water supply phase, and proportion of water processed at the relevant facility. The latter two are associated with the facility (Column B) in the Facility Information Table on the 'Entry-Project Info' worksheet. Allocation factors range from 0 to 1 and will be fractional when the water is processed at multiple facilities.

Fuel Production

Hyperlinks in left columns link to column described.

Fuel Costs per Functional Unit	The Fuel Cost per Functional Unit for each phase (*l*) is calculated for Material Delivery and Equipment Use as follows: $$Cost_l = \sum_{k=1}^{n} FuelUseperFU_{l,k} * FuelUnitCost$$ Where Fuel Use per Fuctional Unit (in gallons) is found in the "Fuel Use" and "Fuel and Electricity Use" Table on the *Calcs-Material Delivery* and *Calcs-Equipment Use* worksheets, respectively. *k* denotes the fuel type (gasoline, diesel, or jet fuel). Fuel Cost is defined on the D*ata-Cost* worksheet (in 1997$/gallon).
Environmental Burden per Functional Unit	Emission (or use for energy) for each category are calculated according to the following equation: $$Emissions_l = EIOLCAEmissionFactor * Cost_l$$ EIOLCA Emission Factors (EFs) are reported in Mg per dollar spent in the sector (or MJ/$ for energy) on the 'EIOLCA EFs' worksheet (Source: EIOLCA 2003). These factors are specific for the Petroleum Refining sector. Cost was calculated in the above section.

Sources:

EIOLCA 2003	Carnegie Mellon University Green Design Initiative. (2003) Economic Input-Output Life Cycle Assessment (EIO-LCA) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 6 Nov, 2003]
EPA 2007	The Emissions and Generation Resource Integrated Database (E-GRID), Version 2.1 files, 2004 data sheets, released May 2007. Accessed May 2007. http://www.epa.gov/airmarkets/egrid/ (for NOx, CO2, and SOx emissions; see "Electricity Emissions" table on *Equipment Use Impacts* worksheet for more information)
Monterey 2003	Monterey County 21st Century General Plan Update Fact Sheet; accesssed 2/10/03 http://www.co.monterey.ca.us/gpu/FactSheets/energy.htm (for CO and energy factors, with DOE 1994; see "Electricity Emissions" table on Equipment Use Impacts worksheet for more information)
DOE 1994	Evaluation of Electricity Consumption in the Manufacturing Division, http://www.eia.doe.gov/emeu/mecs/mecs94/ei/elec.html, accessed 2/10/03. (for CO and energy factors, with DOE 1994; see "Electricity Emissions" table on Equipment Use Impacts
[CBO 2003].	United States Congressional Budget Office, “Prospects for Distributed Electricity Generation”, September. http://www.cbo.gov/showdoc.cfm?index=4552&sequence=4 (Accessed December 6, 2006).

Sludge Disposal Activity

Data Entry Instructions

PURPOSE: This worksheet allows the user to enter sludge disposal data used in the end-of-life phases of the treatment facilities. The activity includes the effects of disposal by landfill or incineration, as well as th effects of associated equipment use and fuel production.

Color convention

Purple	Columns or cells where data should be entered by user
Green	Columns or cells that include drop down menus to be filled in by user
Yellow	Columns or cells where assumptions made should be checked by user
Orange	Columns or cells containing calculations
Pink	Columns containing data entered elsewhere in the spreadsheet
Blue	Columns or cells that include data from other sources and should be verified by user

Hyperlinks in left columns link to column described.

Sludge Data	Facility	Select the treatment facility from the drop-down menu; facilities are defined in the Facilities Table on the "Entry-Project Info" worksheet. Only facilities designated as part of the Treatment phase are included in the list.
	Sludge Volume	Enter the volume of sludge produced in a year in units of tons per year.
	Disposal Facility	Select the type of disposal facility: landfill or incinerator.
	Landfill Gas System	If the disposal facility is a landfill, select the nature of the gas recovery system from the drop-down menu. The options are: No gas recovery, Gas flared, Gas generates electricity, and Unknown. The unknown scenario uses the national average mix of landfill gas systems as described in EPA's WARM model.
	Gas Recovery Efficiency	If landfill gas is specified as flared or used for electricity, select the efficiency of the gas recovery system from the drop-down menu (60%, 75%, 85%, and 95%)
	Distance to Disposal Facility	Enter the one-way distance from the treatment plant site to the disposal facility site in miles.
	Disposal Emission Factors Table	The table summarizes the default emission factors for disposal by incineration and landfill. For landfills, the emission factors also account for the nature and efficiency of the gas recovery system, if present. The emisison factors can be edited by the user as appropriate. The button below the table will restore the default emission factors if changes have been made to the table.

Sludge Disposal Calculations

Hyperlinks in left columns link to column described.

General		Information in this category (Sludge Volume, Disposal Facility characteristics, Distance to Disposal Facility) is obtained from the *Entry-Sludge Disposal* worksheet.
Disposal Calculations	Energy, GWE, NOx, SOx, HC, PM, and CO	The di[...] calculated as follows: $$Burden = \frac{EmissionFactor * SludgeVol * FunctionalUnit}{Annual\ Production}$$ The appropriate emission factor (MG/ton or MJ/ton for energy) is referenced from the table on the Entry-Sludge Disposal worksheet and depends on the type of disposal facility. For landfills, the emission factor also depends on the nature and efficiency of landfill gas recovery. Sludge volume (ton/yr) is defined for the particular facility by the user on the Entry-Sludge Disposal worksheet. The functional unit (AF) and annual production (AF/yr) are defined by the user on the Entry-Project Info worksheet.
Equipment Use Calculations	Energy	[T]he equipment use energy use associated with sludge handing and transport are calculated as follows: $$Burden = \left(\frac{2 * SludgeVol * EnergyFactor * EnginePower}{EquipmentCap * 0.7} + \frac{SludgeVol * 2 * Dist * DieselHeat\ Content}{TruckCap * FuelConsumption * 1000000 * 0.9}\right) * \frac{FunctionalUnit}{Annual\ Production}$$ Where the sum's first term estimates emissions from a loader used to move sludge at plant site and then transfer to a truck (two handlings); the second term estimates transport truck emissions. Sludge volume (ton/yr), functional unit (AF), and annual production (AF/yr) are defined above. The first term includes the energy factor for non-road equipment found on the Equipment Use Impacts worksheet (MJ/hp/hr); engine power (hp) and equipment capacity (tons/hr) based on the loader chosen in the sludge disposal seciton of the Entry-Equipment worksheet; the factor of 2 reflects that the sludge must be handled twice prior to offhaul. An efficiency of 70% is assumed. The second term includes distance from the plant to disposal facility (miles/trip) defined by the user on the Entry-Sludge Disposal worksheet; a factor of two converts one-way distance to round-trip; the diesel heat content of 1.36×10^8 MJ/gal; truck capacity (tons/trip) and fuel consumption (mile/gal) defined on the Entry-Equipment worksheet; the facotr of 1,000,000 J/MJ. 90% efficiency is assumed. The calculation assumes trucks are filled to capacity. User can adjust capacity on the Entry-Equipment sheet to the appropriate value.
	GWE, SOx, Nox, HC, PM, VOCs	The equipment use emissions associated with sludge handing and transport are calculated as follows: $$Burden = \left(\frac{2 * SludgeVol * EmissionFactor * EnginePower}{EquipmentCap * 1000000 * 0.7} + \frac{SludgeVol * 2 * Dist * EmissionFactor}{TruckCap * FuelConsumption * 0.9}\right) * \frac{FunctionalUnit}{Annual\ Production}$$ Where the sum's first term estimates emissions from a loader used to move sludge from settling basin to storage and then transfer to a truck (two handlings); the second term estimates transport truck emissions. Sludge volume (ton/yr), engine power (hp), equipment capacity (tons/hr), distance (miles/trip), truck capacity (tons/trip), fuel consumption (miles/gal), functional unit (AF), and annual production (AF/yr) are defined above. The first term includes the emission factor for non-road equipment found on the Equipment Use Impacts worksheet (g/hp/hr); the factor of 2 reflects that the sludge must be handled twice prior to offhaul. A 70% efficiency is assumed for loader operations. The second term includes a factor of two converts the one-way distance to round-trip; and the emission factor is found in the diesel road emissions table (g/gal). Trucks are assumed to be operated at 90% efficiency. The calculation for transport assumes all trucks are filled to capacity. The user can reduce the capacity of the truck on the Entry-Equipment worksheet to reflect the average capacity of transport trucks if desired. Calculations for PM and VOC only contain the first term related to loader use.
Fuel Production Calculations		Fuel production calculations are described on the Exp-Energy Production worksheet. Click to follow link.
Allocation Factors		Allocation factors are determined by the water source defined in the facility table on the 'Entry-Project Info' worksheet.

Appendix A.1.4:
WESTCalc Companion Tool

This appendix is available as a separate volume,
Appendix_A.1.4_WEST_ Companion Tool.xls

Appendix A.2:
WWEST Tool

This appendix is available as a separate volume,
Appendix_A.2_WWEST_Tool.xls

Appendix A.2.1:
WWEST Manual

WWWEST

Wastewater-Energy Sustainability Tool

User's Manual

Updated: August 1, 2010

Developed by: Dr. Jennifer Stokes and Prof. Arpad Horvath

Department of Civil and Environmental Engineering

University of California, Berkeley

http://www.ce.berkeley.edu/~horvath/WWEST.html

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1.0 Acronyms and Abbreviations

The following summarizes acronyms and abbreviations used in this manual and/or in the WWEST tool.

AS	Activated Sludge	LCA	Life-cycle assessment
Assump	Assumption worksheet	LTRT	Liquid Treatment
Avg	Average	m	Meter
BOD	Biological oxygen demand	M or MMT	Maintenance
C or Con	Construction	m2 or m^2	Square meters
Calc	Calculations	m3 or m^3	Cubic meters
cf	Cubic feet	matl	Material
CH4	Methane	MBR	Membrane bioreactor
cm	Centimeters	MD	Material delivery
CO	Carbon monoxide	Mech.	Mechanical
CO_2eq	Carbon dioxide equivalents	memb	Membrane
Col	Collection	MG	Million gallons
Conv.	Conversions	Mg	Million grams
D	Depth	mg/kg	Milligrams per kilogram
d	Day	mg/L	Milligrams per liter
Def	Default	mi	Mile
Dia.	Diameter	MJ	Megajoules
Dim.	Dimensions	ML	Million liters
Dis	Discharge	ML/d	Million liters per day
EFs	Emission factors	mm	Millimeters
EIO-LCA	Economic Input Output-based LCA	MMBTU	Million BTUs
ENR	Engineering News Record	MP	Material production
EOL	End-of-life	mpg	Miles per gallon
EP	Energy production	MWh	Megawatt-hour
equip.	Equipment	N	Nitrogen
EU	Equipment use	NO_x	Nitrogen oxides
Ext. Aer.	Extended aeration	Nut. Rem.	Nutrient removal
ft	Feet	O or Op	Operation
ft2 or ft^2	Square feet	P	Phosphorus
ft3 or ft^3	Cubic feet	PM or PM_{10}	Particulate matter (less than 10 microns)
g	gram	PPE	Polyphenylene Ether
gal	Gallons	PVC	Polyvinyl chloride
gal/h	Gallons per hour	SBR	Sequencing batch reactors
GHG	Greenhouse gas	SD	Sludge disposal
GWE	Global warming effect (units: CO_2eq)	sf	Square feet
h or hr	Hour	SO_x	Sulfur oxides
hp	Horsepower	STRT	Sludge treatment
in.	Inch	Sys	System
inf	Influent	T or Trt	Treatment
IPCC	International Panel on Climate Change	UV	Ultraviolet
kg	Kilogram	VOC	Volatile organic compound
km	Kilometer	W	Width
kW	Kilowatt	WEST	Water-Energy Sustainability Tool
kWh	Kilowatt-hour	Wksht	Worksheet
l	Liter	WWEST	Wastewater -Energy Sustainability Tool
L	Length	WWTP	Wastewater treatment plant
lb	Pound	yr	Year

2.0 What is WWEST?

The Wastewater-Energy Sustainability Tool (WWEST) is an MS Excel-based tool which can determine some of the environmental effects of wastewater system infrastructure and operation. A companion tool, the Water-Energy Sustainability Tool (WEST), evaluates the effects of water infrastructure and operation.

WWEST incorporates life-cycle assessment (LCA), a proven methodology for systematically quantifying cradle-to-grave material and energy inputs and air emissions. The tool requires user input for the construction and maintenance phases, equipment use, and electricity consumption for a wastewater supply system. Based on the input, WWEST estimates air emissions. Environmental effects calculated include: energy consumption and emissions of greenhouse gases (GHGs, and CO_2 equivalents as the global warming effect [GWE]), nitrogen oxides (NO_x), particulate matter smaller than 10 microns (PM_{10}), sulfur oxides (SO_x), carbon monoxide (CO), and volatile organic compounds (VOC). Select additional emissions to air and water are also available in the tools.

WWEST provides the results according to the associated life-cycle phase (construction, operation, maintenance, or end-of-life), the wastewater system phase (collection, treatment, or discharge), and life-cycle activity (material production, material delivery, equipment use, energy consumption, direct emissions, sludge disposal). Table 1 defines these categories. The activities are defined in additional detail in Section 4.0.

WWEST is designed to be used by water system designers, utility operators, civil engineers, consultants, and researchers. Users should have a working knowledge of wastewater systems, data related to a real or hypothetical wastewater utility, and a desire to learn more about the environmental implications of their decisions.

Phase/Category		Description
Life-cycle	Construction	Includes energy use & emissions from producing construction materials, treatment equipment, & energy used in initial installation, including supply chains; fuel use & emissions from construction equipment & delivery vehicles
	Operation	Includes energy & emissions from collection, treatment, & discharge; energy generation offsets from treatment; fuel use & emissions from delivery & operational vehicles; energy use & emissions from producing chemicals & other routinely used materials (including supply chains); direct emissions from the treatment process
	Maintenance	Includes energy use & emissions from producing replacement parts for components with service lives shorter than the analysis period (including supply chain); fuel use & emissions from maintenance & delivery vehicles
	End-of-life	Includes fuel use & emissions for transporting & disposing of sludge; long term emissions, energy generation offsets, & coproduct offsets from disposal (e.g., fertilizers). Decommissioning water infrastructure contributes <0.01% to overall results [22]; wastewater results are expected to be similar, thus were not calculated
System	Collection	Transporting sewage from consumer to the treatment plant, & related infrastructure
	Treatment	Ensuring effluent meets regulatory standards & necessary infrastructure; includes liquid & sludge treatment
	Distribution	Transporting treated effluent to the discharge point & required infrastructure
Activity	Material production	Quantifies materials used in the system & the energy/environmental effects of their manufacture & provision; primarily uses EIO-LCA combined with process-based LCA
	Material delivery	Assesses the energy used & emissions from transportation of materials by truck, train, ship, or airplane; uses process-based LCA
	Equipment use	Evaluates emissions & fuel use from operating non-transport construction equipment & maintenance vehicles; uses process-based LCA
	Energy production	Quantifies effects of electricity production & fuel production (e.g., gasoline, diesel) needed to operate vehicles; uses process-based LCA for electricity & EIO-LCA for fuel
	Direct emissions	Estimates the GHG emissions from treatment processes which exceed the inevitable biogenic CO_2 emissions; uses process-based LCA
	Disposal	Analyzes the effects of transporting & disposing of sludge; uses process-based LCA

Table 1: Category Definitions [Adapted from (Stokes and Horvath 2010)]

3.0 What knowledge will I gain from using WWEST?

WWEST users may enter data about an existing, proposed, or hypothetical wastewater system to determine the environmental effects of their decisions. The tools can inform decisions such as:

- MATERIAL SELECTION: For a particular pipeline installation, is steel or plastic pipe better for the environment?
- PROCESS SELECTION: Is it preferable to implement membrane or traditional filtration? Which disinfection method is more environmentally detrimental: chlorine, ozone, or ultraviolet (UV) light?

- ENERGY SOURCE SELECTION: What percentage of the environmental effects associated with my utility is associated with material production or electricity use? What if all our electricity came from solar power, how much would that reduce emissions?
- SUPPLIER SELECTION: How much can we reduce our environmental effects by purchasing from local suppliers? Using different chemicals?

This list of questions is not comprehensive but gives an idea of the types of issues that WWEST can be used to evaluate. In addition, it is possible to customize WWEST to get more specific results as needed. For example, custom calculations can be created to isolate the results for a particular treatment process and compare them to an alternate process or to utilize two different electricity mixes within the system.

4.0 What is the methodological basis of WWEST?

WWEST combines the power of two proven LCA approaches: process-based LCA and economic input-output analysis-based LCA (EIO-LCA).

Process-based LCA is outlined in the International Organization of Standardization's 14040 standards (Intergovernmental Panel on Climate 2006). In order to get specific and localized results, process-based LCA requires the practitioner to collect all needed data on energy and resource inputs and environmental outputs from any available sources (e.g., system operators, product manufacturers, industry experts, and available literature). As a result, it can be data-, time-, and cost-intensive. Some publicly- available sources provide process-based results for certain products. For example, PlasticsEurope provides information about manufacturing some plastic products and intermediary chemicals in Europe (PlasticsEurope 2010).

EIO-LCA was created by the Green Design Initiative at Carnegie Mellon University and can be accessed on-line at http://www.eiolca.net (Carnegie Mellon Green Design Institute 2007). It utilizes the U.S. economy's input-output matrix to comprehensively map the interactions between economic sectors and define product and service supply chains. These economic data are combined with publicly-available environmental data (e.g., resource consumption and environmental emission and waste data) When the user inputs a producer's expenditure in a particular economic sector, the model evaluates how much is spent directly in that sector and its supply chain and calculates the corresponding environmental emissions and wastes associated with the specified expenditures. EIO-LCA can be used to get an estimate of environmental effects based only on material and energy cost (PlasticsEurope 2010).

The structure of WWEST is shown in Figure 1. WWEST incorporates elements from both process-based LCA and EIO-LCA, as delineated in Table 1 and Figure 1. Generally, EIO-LCA is used to determine the effects of material production and process-based LCA is used to evaluate material delivery, equipment operation, and energy production.

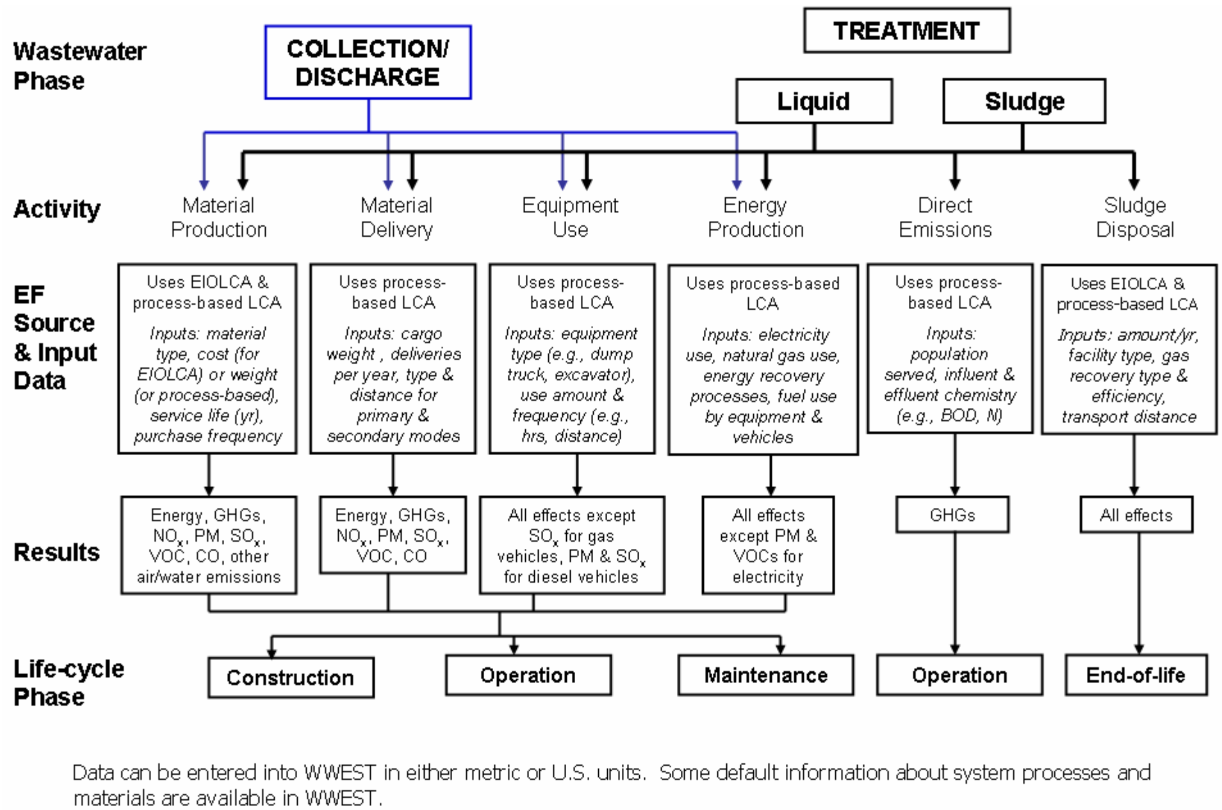

Figure 1: WWEST Structure

A hybrid LCA approach incorporates data from a variety of sources including: the on-line EIO-LCA tool for material production emissions, the Environmental Protection Agency's Emissions and Generation Resource Intregrated Database (E-GRID) (USEPA 2007) for electricity generation emissions and AP-42 standards for diesel engines (USEPA 1995), the Caterpillar and other manufacturers for equipment data (e.g., (Caterpillar Inc. 1996)), the California Air Resources Board's Off-Road Emissions Model for construction equipment emissions (California Air Resources Board 2002), published LCAs, and others. Detailed referencing is available in the background data sheets of the WWEST tool and is described in (Stokes and Horvath 2010) as well as in the final report for this project.

5.0 What are the "activities" analyzed in WWEST?

As Figure 1 shows, WWEST focuses on six activities that contribute to the environmental effects of a wastewater system. Any or all of these can be used in a particular analysis. The six activities are: material production, material delivery, equipment use, energy production, direct emissions, and sludge disposal. Each activity is described further below.

5.1. Material Production

The Material Production activity estimates the impact of extracting, transporting, processing, and manufacturing materials from “cradle to gate”, i.e., from the raw material extraction until the final product is ready to leave the door of the manufacturer. It can be used to analyze a wide variety of materials, including: concrete, pipe, pumps, electrical equipment, chemicals, steel tanks, and membranes. This module uses emission factors (EFs) from EIO-LCA in combination with some process-based information from databases from PlasticsEurope and/or GaBi (GaBi 2005; PlasticsEurope 2010), primarily for plastics and chemicals. The specific sources are cited within the tool on the “AirEFs” and “WaterEFs” worksheets. Table 2 shows the default materials included in WWEST as well as related assumptions.

Material	Delivery Distance (km)	Service Life (yrs)	Process/ EIOLCA	Material	Distance (km)	Life (yrs)	Process/ EIOLCA	Material	Distance (km)	Life (yrs)	Process/ EIOLCA
Acid, carbonic	193	1	EIOLCA	Fans	515	15	EIOLCA	Pipe, ductile iron	257	75	EIOLCA
Acid, hydrochloric	193	1	EIOLCA	Ferric chloride	193	1	EIOLCA	Pipe, metal	257	75	EIOLCA
Acid, sulfuric	193	1	EIOLCA	Ferric sulphate	193	1	EIOLCA	Pipe, HDPE	257	50	EIOLCA
Acids, inorganic	193	1	EIOLCA	Ferrous sulphate (copperas)	193	1	EIOLCA	Pipe, plastic	257	50	EIOLCA
Activated carbon	322	1	EIOLCA	Fibers, manmade celluosic	1931	6	EIOLCA	Pipe, PVC	257	50	EIOLCA
Activated charcoal	322	1	EIOLCA	Fluid Power Equipment	515	1	EIOLCA	Pipe, stainless steel	257	75	EIOLCA
Adhesives	97	1	EIOLCA	Frames, metal	257	60	EIOLCA	Pipe, steel	257	75	EIOLCA
Adjustable frequency drives	1287	15	EIOLCA	Gaskets	97	2	EIOLCA	Pipe, vitrified clay	257	60	EIOLCA
Aggregate (filter media)	322	3	EIOLCA	Gasoline	322	1	EIOLCA	Plastic hose & belts	129	3	EIOLCA
Aggregate (not filter media)	193	100	EIOLCA	Generators	1609	15	EIOLCA	Plastic molding	193	15	EIOLCA
Alkalis	193	1	EIOLCA	Generators, turbine	1609	30	EIOLCA	Plastic products, misc.	193	15	EIOLCA
Alum	193	1	EIOLCA	Glass products	161	15	EIOLCA	Plastic resins	290	6	EIOLCA
Aluminum chloride	193	1	EIOLCA	Gravel aggregate	257	100	EIOLCA	Polyaluminum chloride	193	1	EIOLCA
Aluminum sulfate	193	1	EIOLCA	Gravel filter media	322	3	EIOLCA	Polyiron chloride	193	1	EIOLCA
Ammonia, aqueous	193	1	Process	HDPE resins	386	30	EIOLCA	Polymers	290	50	EIOLCA
Ammonium compnds	193	1	EIOLCA	Hydrated lime (dolomitic)	193	1	EIOLCA	Polypropylene	193	75	Process
Anthracite	4023	3	EIOLCA	Hydrogen peroxide	193	1	EIOLCA	PPE resins	290	75	EIOLCA
Asphalt	129	20	EIOLCA	Industrial equipment, electrical	515	100	EIOLCA	Pump intake screens	161	3	EIOLCA
Blowers	483	15	EIOLCA	Industrial equipment, general	515	25	EIOLCA	Pumps	515	15	EIOLCA
Brick	97	100	EIOLCA	Ion Exchange resins	3862	2	EIOLCA	Pumps, metering	644	5	EIOLCA
Building maintenance	97	5	EIOLCA	Iron forgings	257	100	EIOLCA	PVC resins	290	6	EIOLCA
Buildings; office, ind, & comm	322	60	EIOLCA	Jet fuel	322	1	EIOLCA	Rebar	193	100	EIOLCA
Calcium carbonate	193	100	EIOLCA	Joint compounds	161	60	EIOLCA	Reinforced concrete	193	100	EIOLCA
Calcium hypochlorite	193	5	EIOLCA	Laboratory equipment	515	8	EIOLCA	Riprap	241	100	EIOLCA
Calcium oxide	193	1	EIOLCA	L&scaping	129	12	EIOLCA	Rubber hose & belts	97	2	EIOLCA
Carbon dioxide	193	1	EIOLCA	Light bulbs & tubes	97	2	EIOLCA	Rubber, synthetic	97	20	EIOLCA
Cardboard	97	1	EIOLCA	Light fixtures & equipment	322	15	EIOLCA	S& filter media	322	3	EIOLCA
Cartridge filters	322	2	EIOLCA	Lime (Calcium hydroxide)	193	1	EIOLCA	Sealants	97	5	EIOLCA
Caustic soda	193	1	Process	Limestone	241	1	EIOLCA	Sealing devices	97	3	EIOLCA
Chemicals, general	193	1	EIOLCA	Lubricants	193	12	EIOLCA	Soda ash	193	1	EIOLCA
Chemicals, industrial	193	1	EIOLCA	Lumber	129	40	EIOLCA	Sodium aluminate	193	1	EIOLCA
Chemicals, inorganic oxidizers	193	1	EIOLCA	Magnesium hydroxide	193	1	EIOLCA	Sodium bicarbonate	193	1	EIOLCA
Chemicals, water treatment	193	1	EIOLCA	Magnesium oxide	193	1	EIOLCA	Sodium bisulfite	193	1	EIOLCA
Chloramine	193	1	EIOLCA	Membrane, cellulose acetate	1931	6	EIOLCA	Sodium hypochlorite	193	1	EIOLCA
Chlorine	193	1	Process	Membrane, PSU	1931	6	EIOLCA	Sodium metabisulfite	193	1	EIOLCA
Clay (as construction material)	257	60	EIOLCA	Membrane, PVDF	1931	6	EIOLCA	Sodium sulfate	193	1	EIOLCA
Clay tile, structural	97	60	EIOLCA	Meters, flow	1287	15	EIOLCA	Sodium sulfite	193	1	EIOLCA
Coal	4023	60	EIOLCA	Molding & trim, metal	257	60	EIOLCA	Sodium thiosulfate	193	1	EIOLCA
Compressors	515	10	EIOLCA	Mortar	322	40	EIOLCA	Steel forgings	257	100	EIOLCA
Computers	257	4	EIOLCA	Motors	515	15	EIOLCA	Steel railings	161	50	EIOLCA
Concrete additives	129	100	EIOLCA	Natural Gas	193	1	EIOLCA	Steel, raw	257	100	EIOLCA
Concrete block	193	100	EIOLCA	Office furniture, non-wood	161	15	EIOLCA	Street maintenance	161	10	EIOLCA
Concrete products, other	386	100	EIOLCA	Office furniture, wood	161	15	EIOLCA	Streets	225	20	EIOLCA
Concrete, precast	386	100	EIOLCA	Oil & lubricants	97	1	EIOLCA	Sulfur dioxide	193	3	EIOLCA
Concrete, ready-mixed	129	100	EIOLCA	Oil fuel	193	1	EIOLCA	Tanks, bolted steel	1287	50	EIOLCA
Construction equipment	290	10	EIOLCA	Oxygen	193	1	EIOLCA	Tanks, other steel	1287	50	EIOLCA
Controls	386	15	EIOLCA	Ozone	0	1	EIOLCA	Trucks, Industrial	515	10	EIOLCA
Crude petroleum	644	10	EIOLCA	Packing devices	483	3	EIOLCA	Turbines	1931	30	EIOLCA
Diesel	322	1	EIOLCA	PAN- fiber reinforced products	193	1	EIOLCA	Valves & fittings, metal	257	15	EIOLCA
Doors, metal	257	40	EIOLCA	Petroleum products	161	1	EIOLCA	Valves & fittings, plastic	257	10	EIOLCA
Drilling mud	193	1	EIOLCA	PEI	1931	1	EIOLCA	Wood	129	50	EIOLCA
Electrical equipment	386	15	EIOLCA	Pipe sealing compounds	161	30	EIOLCA	Zinc orthophosphate	193	1	EIOLCA
Electrical wire	97	1	EIOLCA	Pipe, cast iron	257	75	EIOLCA	Tanks, redwood	129	50	EIOLCA
Electronics, office	322	4	EIOLCA	Pipe, concrete	257	75	EIOLCA	Wood pump stations	129	50	EIOLCA
Epoxies	97	5	EIOLCA	Pipe, DI- lined/coated	257	75	EIOLCA				

Table 2: Material Summary and Default Data

Service lives of materials are also listed in Table 2. The calculations use this information to determine how many times each material will be purchased during the analysis period. For example, if the analysis period is 25 years, pumps with a service life of 15 years will be purchased once at the time of construction and once at the end of the service life. Two-thirds of the impacts for the second purchase will be classified in the maintenance category because ten of the fifteen years of the pump's life is in the analysis period. If the service life is longer than the analysis period, the material will only be purchased once at the time of construction.

5.2. Material Delivery

This activity calculates the impacts of transporting materials from the point of manufacture to the point of final use. The following modes of transportation can be evaluated: local truck, long-distance truck, train, ship, and plane. The user can evaluate a primary and secondary mode of transportation. The secondary mode can be used when transportation is used serially, i.e., when product is off-loaded from a train to a local truck. Default delivery distances exist for all materials but should be reviewed and edited by the user.

5.3. Equipment Use

The Equipment Use section calculates the tailpipe emissions from construction equipment, maintenance vehicles, and personal-use vehicles. Some equipment that can be analyzed include: concrete mix truck, small and large excavator, backhoe loader, wheel loader, vibratory roller compactor, grader, dozer, dump truck, forklift, crane, generator, tanker truck, paver, sedan, and pickup truck. Personal-use vehicles are included to analyze passenger cars included in the utility's fleet, if applicable, and can also be used to analyze the effects of commuting if the user is interested.

5.4. Energy Production

Energy production includes the effects of electricity generation, natural gas combustion, and fuel production for gasoline and diesel. Natural gas is used by utilities to operate pumps and turbines, for example. Fuels are used in on-site equipment like generators or in vehicles. For electricity consumption, the user can select whether they will use direct emissions (i.e., smokestack) or life-cycle emissions which also includes the supply chain. The user can also choose between EFs for the national average energy mix, state-specific energy mix, or a custom energy mix which uses a combination of coal, oil, natural gas, other fossil fuels (e.g., blast furnace gas, coke oven gas, methanol), hydroelectric, nuclear, biomass, wind, geothermal, and solar. In addition, the user can enter custom EFs for their site. Natural gas combustion EFs are also available and can be customized.

Users can also enter information related to energy recovery by methane combustion. The assumed EFs for electricity combustion from methane is assumed to be equivalent to the direct emissions for natural gas, except for the GHG EF. The direct emissions are used because no fuel mining or transport are needed. Therefore indirect emissions are assumed to be negligible. The GHG emissions are assumed to be zero. The fuel source is sewage, therefore, biogenic. The decomposition to CO_2 is inevitable and can therefore be ignored. However, the electricity recovered offsets the use of electricity from dirtier sources and therefore results in a net reduction in emissions if default values are used.

The effects of producing fuels for vehicles and equipment are included as well. The emissions associated with fuel production are calculated automatically based on inputs to the equipment use worksheet. No additional data must be entered for this category. However, the EFs can be edited by the user, if desired.

5.5. Direct Process

WWEST provides default values for process emissions depending on the treatment processes included in the WWRP. The methane is produced from anaerobic decomposition of sludge, either intentional or incidental. The default EFs for treatment processes are from the IPCC (Intergovernmental Panel on Climate 2006). The user can refine the final emission values by defining the CH_4 capture rate for the treatment plant. The user can edit the default emissions if better information is available.

5.6. Sludge Disposal

Sludge disposal includes the effects of collecting, transporting, and disposing of sludge produced in the treatment process. The scenario assumes a wheel loader will be used to collect and move the soil onsite and that all sludge will be handled twice, once at the utility location and once at the landfill. A dump truck is assumed to be used to transport waste. The user can define the delivery distance and the nature of the disposal facility. WWEST contains EFs for landfills, land application, and incinerators. The user can edit these EFs or enter EFs for an alternative disposal scenario.

6.0 What data are needed to use WWEST?

Figure 2 summarizes the types of input data needed to analyze each activity included in the WWEST tool. Not all users will be interested in using all aspects of the tool. Users should determine which components and activities are of most interest to them and focus their time and resources on obtaining the necessary data to complete those components. For example, a utility may only be interested in understanding the GHG emissions associated with electricity production and will therefore be able to ignore data entry for all but the general information and energy production sheets. If a utility is also interested in analyzing the effects of their treatment chemical consumption, data about their annual chemical consumption should also be entered on the material production page. If the utility wants a more comprehensive analysis, the user may choose to include an inventory of capital materials in the entire system, or perhaps for a particular aspect of the system (e.g., filtration equipment), and will need to input costs for that equipment in the tool.

Default values are present for many calculations. For example, a user may enter the length of pipe in their collection system and calculate the effects of manufacturing and installing those pipelines automatically. Also, a user may enter the population served by the WWTP, select the treatment processes in the plant, and get a rough estimate of the effects of the associated infrastructure.

7.0 How do I start using WWEST?

The following sections describe the WWEST tool and are intended to help the reader utilize the tool, but do not fully detail all the background assumptions, data sources, calculations and references. If you are interested in more specific information included in the tool, including equations, please refer to:

- the WWEST documentation included in the tool,
- the final project report to the California Energy Commission for Project MR-06-08 (available early 2011 on the Energy Commission's website); and
- Stokes, J. and A. Horvath (2010). "Supply-chain environmental effects of wastewater utilities." Environmental Research Letters **5**(1): 014015.

There are five types of worksheets in WWEST: entry, results, explanatory, calculations, and background worksheets. Each worksheet type is described in the following sections.

7.1. Entry Worksheets

The tool takes the user through a series of input worksheets to gather data about:

- The general system (e.g., location, sources of water, facilities such as treatment plants)
- Initial construction and maintenance materials as well as material transportation distances and modes
- On-site construction equipment (e.g., excavator, loader)
- Electricity consumption and recovery
- Sludge disposal

Data entry is classified by wastewater phase (collection, treatment and disposal) and separately for energy EFs. For each wastewater phase, a required entry page is present as well as an "Assumption (ASSUMP)" page which allows for more specific and detailed data entry. Two ASSUMP pages are present for treatment, one for liquid and one for sludge treatment. For each data entry page, a list of required data needed to complete the page is provided. A sample list of optional data for a utility is also provided.

The color convention for data entry cells in WWEST are as follows:

- The user should enter data in the PURPLE cells.
- The user should select an option from a drop-down menu in the GREEN cells.
- WWEST automatically reads in data from elsewhere in the tool in YELLOW cells; the user can update as needed. These cells are typically locked so the user does not inadvertently change the data.
- WWEST automatically calculates values in TAN cells; the user can update as needed. These cells are typically locked so the user does not inadvertently change the data.

Hyperlinks (blue underlined text) refer to cells which describe the data which should be entered into the cell and, if relevant, provide equations used.

TIP: DO **NOT** SORT data or DELETE lines out of entry tables. Data can be deleted out of specific lines but do not change the structure of the table itself. This will cause calculation errors.

TIP: Enter data in order as you go through the worksheets. If you must go back and make a change, be aware that clicking the "Enter Data" button at the bottom of each entry page may cause user-entered data on subsequent pages to be deleted. Copy user-entered data from later pages onto a separate sheet or into a separate workbook so it is not lost.

7.1.1. General Data Entry

Required data: Analysis period, functional unit, system name, project location, population served, annual wastewater production and design capacity for WWTPs.

Optional data: System acronym, service area size

Figure 3 shows the Project Information worksheet which collects the general inputs about the water system. The sheet is filled in with hypothetical data for demonstration purposes. A button at the top of the page can be clicked to reset default data, if needed. Note that clicking this button will clear all user-entered data. The cells on this worksheet are described below.

Model information table:

- UNIT SELECTION: Select the desired units (U.S. or metric) of entry from the drop-down menu. Changing the value will trigger a macro that will revise the entry pages to show the user what units to enter.
- ANALYSIS PERIOD: Defines the time period over which analysis occurs. The analysis period should be selected appropriately for the materials being analyzed. If capital materials are analyzed, an analysis period of 20-30 years may be used to represent the planning horizon for the facility. The user may also reasonably select an analysis period equivalent to the longest service life in the system (e.g., up to 100 years for concrete materials). Regardless of the analysis period chosen, the WWEST calculations will account for additional purchase of materials with service lives shorter than the analysis. Purchases of materials with services lives longer than the analysis period are discounted accordingly. If the user is only interested in consumable materials such as electricity, fuels, and chemicals, the selection of an analysis period is irrelevant and an analysis period of 1 year may be appropriate. This is a required input.
- FUNCTIONAL UNIT: Defines the volume of wastewater to which all results will be normalized. The user may select a round functional unit (i.e., one million gallons [MG] or million liters [Ml]) or one that is significant in the analysis (i.e., the amount of wastewater processed annually by the facility being analyzed). This is a required input.

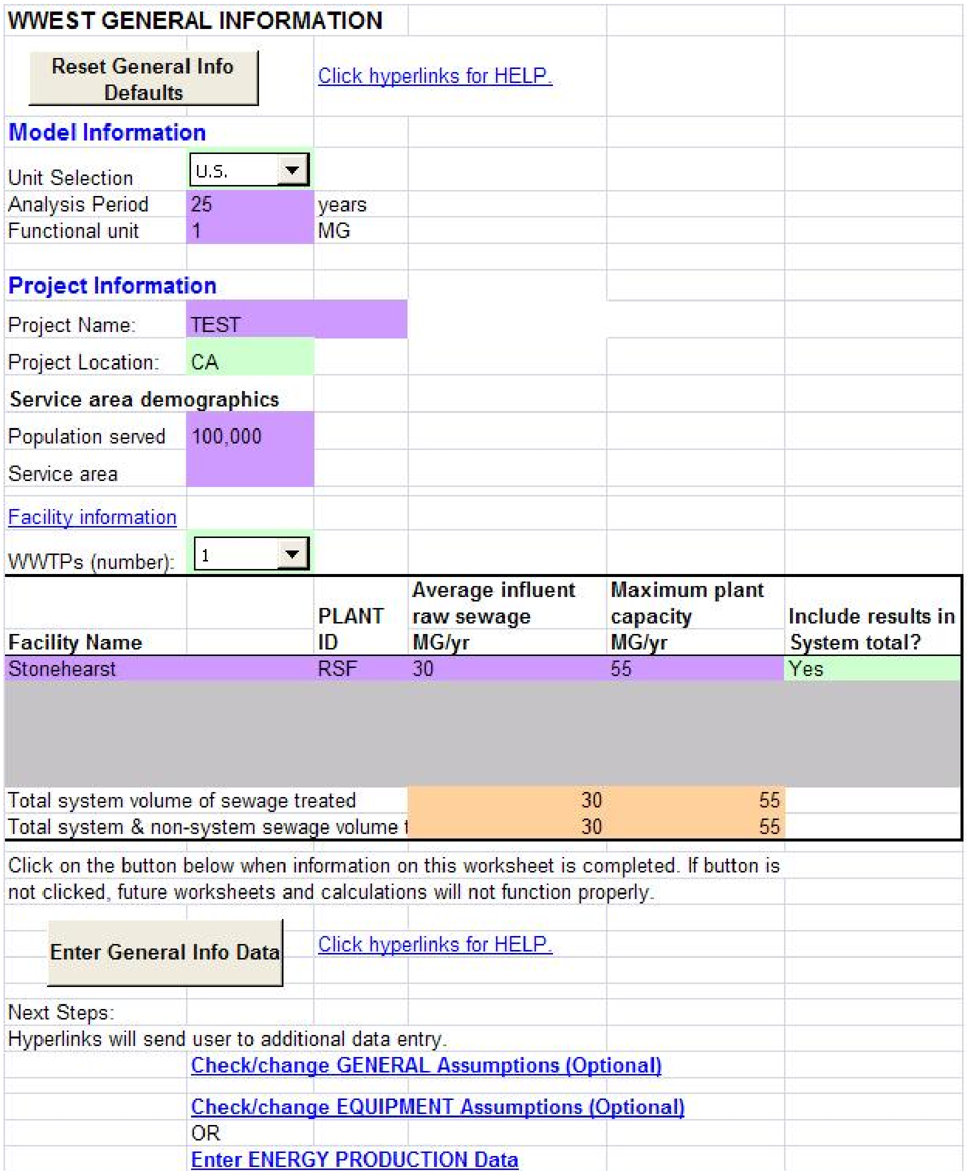

Figure 2: ***Entry- General*** **Worksheet**

Project Information:

- PROJECT NAME: Defines the utility to be analyzed.
- PROJECT LOCATION: Allows the user to select the state where the utility is located from a drop-down menu. This is a required input.

Service area demographics: Allows the user to input information about the service area and customer break-down of the utility. The population served input is required. The service area is optional.

Facility Information: The facility table defines the WWTPs in the system. It can include different sections of pipeline or aqueduct, different treatment plants, or different sections of the distribution system. The user should select the number of WWTPs needed for the analysis. The selection will trigger a macro that will shade in unnecessary cells. The following are columns in the facility table.

- FACILITY NAME: The user can define a name for each WWTP.
- PLANT ID: The user can enter a shortened version of each plant name for easier viewing in table. Entry into this column is required.
- AVERAGE INFLUENT RAW SEWAGE: Enter the volume of wastewater treated in a particular year or an average year for each of the facilities defined. This number will be used to normalize the results to the defined functional unit.
- MAXIMUM PLANT CAPACITY: Enter the design capacity for the WWTP. The value will be used to create the default sizes for treatment processes.
- INCLUDE IN TOTAL?: Select "yes" if this WWTP should be included in the results for the system being analyzed. Select "no" if the WWTP should be excluded from the results for the overall system. A user might want to analyze their existing infrastructure to get a baseline, or system, result but also analyze a possible new design as a separate facility that will not be included in the baseline results. In that case, the user would select "No" for the facilities included only in the new design.

The user must click the "Enter General Info Data" button at the bottom of the page to trigger a macro which will revise default calculations and additional entry pages based on the user's selections. The hyperlinks at the bottom of the page can be used to guide the user through additional entry pages.

7.1.1. General Assumptions

All entries on this page ("ASSUMP-Gen") are optional. The user can revise assumptions about materials used in construction, operation, and maintenance. Clicking the button at the top of the page will reset the default assumptions, if needed.

Model Information: The GWE time horizon used in the tool (100 years) is shown. The current year is automatically entered. The user can define the year that typical costs are reported in. The default value is 1997. All costs are normalized to 1997 dollars to use with the EIOLCA EFs.

Material Delivery Detail and Custom Materials: This table can be revised to change the assumptions used in material production and delivery calculations as well as to define custom materials that are not included in the WWEST tool. Scroll to the bottom of the list to enter custom materials. The columns are defined as follows:

- SERVICE LIFE: Revise the number of years each material is expected to last on average. Consumable materials should have a service life of one.
- PRIMARY and SECONDARY DELIVERY MODE: Select the appropriate delivery mode from the drop-down menu (local truck, long distance truck, ship, train, or plane). A secondary mode may

be needed if the material are delivered by ship, train, or plane and must be transferred to a truck for final delivery.

- PRIMARY and SECONDARY DELIVERY DISTANCE: Enter the distance that the material must be transported from the point of manufacture or production to the point of use.
- CUSTOM MATERIALS SECTOR: For custom materials, the user should select the appropriate economic sector from the drop-down menu. For guidance, see the documentation for the EIO-LCA tool to determine how materials are categorized into sectors.

Click the “Enter General Assumptions Data” button after changes are made to make necessary revisions to future calculations.

7.1.1. Equipment Assumptions

All entries on this page (Assump-Equip) are optional. The user can revise assumptions about equipment used in construction, operation, and maintenance and enter data about custom equipment. Clicking the button at the top of the page will reset the default assumptions, if needed.

Equipment Data Entry: This table can be revised to change the assumptions used in equipment use calculations as well as to define custom equipment not included in the WWEST tool. Scroll to the bottom of the list to enter custom equipment. The columns are defined as follows:

- TYPICAL BRAND/MODEL: Enter or revise a model that is typical for the assumptions entered.
- ENGINE CAPACITY: Enter the engine capacity for the equipment, as appropriate.
- POWER: For electricity-powered equipment, enter the electric rating (in watts).
- UNITS: The units will be entered automatically. For off-road equipment, the unit is hours (i.e., all EFs are in units of MJ or g per hour). For on-road equipment, the unit is distance. For custom equipment, select hours or distance from the drop-down menu.
- FUEL CONSUMPTION: Enter or revise the fuel consumption for the equipment in the units indicated.
- FUEL TYPE: Select the type of fuel used in the equipment (diesel, gasoline, electric, or other fuel which can be defined on the Entry-Energy Mix page).
- ENERGY USE AND EMISSIONS: Enter or revise the emission factor for energy use and air emissions, as appropriate.

Equipment Efficiencies: Revise the efficiencies applied to construction equipment and trucks, as appropriate. The default value for construction equipment is 60% (i.e., the equipment is idle or unproductive four out of ten hours). For trucks, the value is assumed to be 80%.

It is unnecessary to trigger a macro for this data to be used in the tool.

7.1.2. Energy Production

The, *Entry-Energy Mix,* is used to enter information about the electricity mix and also to edit EFs for natural gas combustion and fuel production. Figure 3 shows the *Entry-Energy Mix* worksheet. Defaults are present for all the inputs of this page. Edits are optional. The following describes the inputs on this page:

Electricity Mix Selection:

- DIRECT OR LIFECYCLE EMISSION FACTORS: Select whether to use EFs for direct (i.e., smokestack) or life-cycle (i.e., including supply chain) emissions. The default value is lifecycle emissions.
- SCENARIO: Select the desired electricity mix from the drop-down menu. The choices are: State average mix, National average mix, and Custom generation mix. The default value is State-average Mix which is selected based on the location entered on the *Entry-Project Info* worksheet.

Reset ENERGY PRODUCTION defaults

Click hyperlinks for HELP.

Energy consumption information is entered on the Wastewater Phase Entry Pages.

Energy Mix Selection

Emission Factors: Lifecycle Emissions

Electricity Scenario: Custom Generation Mix

Electricity Default Data and Emission Factors

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

	State Average Mix	Mix Contributions and Source-Specific Emission Factors									
		Coal	Oil	Natural Gas	Nuclear	Other Fossil Fuels	Hydro	Biomass	Wind	Solar	Geo-thermal
Assumed Distribution Loss	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Contribution of Source		8%		39%	22%		19%	4%	2%	1%	5%
Life-cycle Emission Factors (g/kWh, unless noted)											
Energy Use (MJ/kWh)	6.9	10.3	9.0	8.6	11.5	9.0	1.73	0.43	0.29	0.64	0.59
GHG	388	1017	559	669	17	591	24	245	31	48	28
NO_x	0.3	1.7	1.24	0.60	0.065	1.6	0.025	1.9	0.019	0.34	0.19
PM	0.081	4.7	3.0	2.1	0.0223	0.2	0.0070	1.1	0.043	0.34	0.062
SO_x	1.1	0.02	0.02	0.4	0.000		0.0060	0.34	0.010	0.07	
VOCs	0.20	3.231	0.134	0.07	0.005		0.0050	0.15	0.012	0.080	0.04
CO	0.32	0.12	0.24	0.55		0.24	0.100	0.08	0.097	0.11	0.21

Natural Gas Emission Factors (MJ or g/MBTU)

Additional information on Natural Gas emission factors found here.

Energy Use	1058
GHG	62122
NO_x	74
PM	4.9
SO_x	17.47
VOC	13
CO	63

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

	Gasoline	Diesel	Other	Other	Other
Energy Use	32	25			
GHG	2438	2432			
NO_x	5.8	5.7			
PM	1.3	1.2			
SO_x	2.9	2.8			
VOC	3.4	1.0			
CO	1.7	1.7			

Biogenic Methane Emission Factors (MJ or g/kWh)

Default values ssumed to be the same as direct natural gas electricity generation above except for greenhouse gases

Energy Use	3.6
GHG	0
NO_x	0.24
PM	0
SO_x	0.049
VOC	0
CO	0.24

Figure 3: *Entry-Energy Mix* Worksheet

Default or User-Defined Data and Emission Factors.

Based on the selections made, cells in these tables which are relevant to the calculations will be left clear while others are grayed out.

- ASSUMED DISTRIBUTION LOSS: The user can edit the assumed transmission and distribution losses. The default value is 10%. A hyperlink to reference information on electricity system losses is present above the table, if needed.
- CONTRIBUTION OF SOURCE: When a customized generation mix is selected, the user should enter the percentage contribution from each source. If the values sum to less than 1, the remainder of the electricity is assumed to come from the state-average mix.

The remainder of the table is composed of default EFs for each possible electricity source. In the default values table, the values are provided for reference only. They can be edited in the lower table.

Natural Gas and Fuel Emission Factors. These tables provide default data for direct combustion of natural gas as well as production of fuels such as gasoline and diesel that will be used in vehicles and equipment. The user can enter other fuels as desired. Additional EFs for fuels (e.g., biodiesel, ethanol, fuel cells) can be found on the Fuel EFs worksheet in the background information

Biogenic Methane Emission Factors. This table provides EFs for biogenic CH_4 if it is used on-site for electricity generation. The EFs are assumed to be equal to the direct emissions from natural gas combustion for electricity. The direct emissions are used because the CH_4 will not need to be mined or transported so indirect effects are negligible. The GHG EF is assumed to be zero because the fuel source (sewage) is biogenic so it will inevitably decomposed to CO_2 so it is not counted against the utility.

7.1.3. COLLECTION and DISCHARGE Entry

The collection and discharge system entry pages (Entry-COL and Entry-DIS, respectively) are similar and therefore discussed together. Information about pipe length, valves, and flowmeters, manholes and curb inlets (for the collection system only), lift stations and pumps, and energy consumption. 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. Data can be entered for the "System" or assigned to a specific WWTP. If data is entered as part of the overall system, the results will be associated with all WWTPs that are also included in the system. In general, most of the pipeline will be included in the system category. The user may want to enter information for a specific facility if it is only used to connect to that WWTP or if the user is analyzing a separate "non-system" scenario and collection or discharge pipeline is included in the analysis.

Figure 4 shows a partial view of Discharge (Entry-DIS) data entry page. The user enters data about infrastructure, equipment, and energy use.

The following describes data entry for the Entry-COL and DIS worksheet for construction:

Pipeline Material Production Estimates. Pipeline data is summarized by diameter ranges, three categories for Collection pipe and two for Discharge pipe. For the overall system and for each of the WWTPs, the user can enter the pipe length and number of valves.

Pipeline Material Breakdown. For each of the diameter ranges, estimate the percentage of pipeline made of each of the following materials: concrete, vitrified clay, ductile or cast iron, PVC, or other plastics. The sum of the percentages must equal 100%. If the system contains pipe of another material, the user can select the most appropriate alternative or can enter the pipeline in the Additional Material Entry table below.

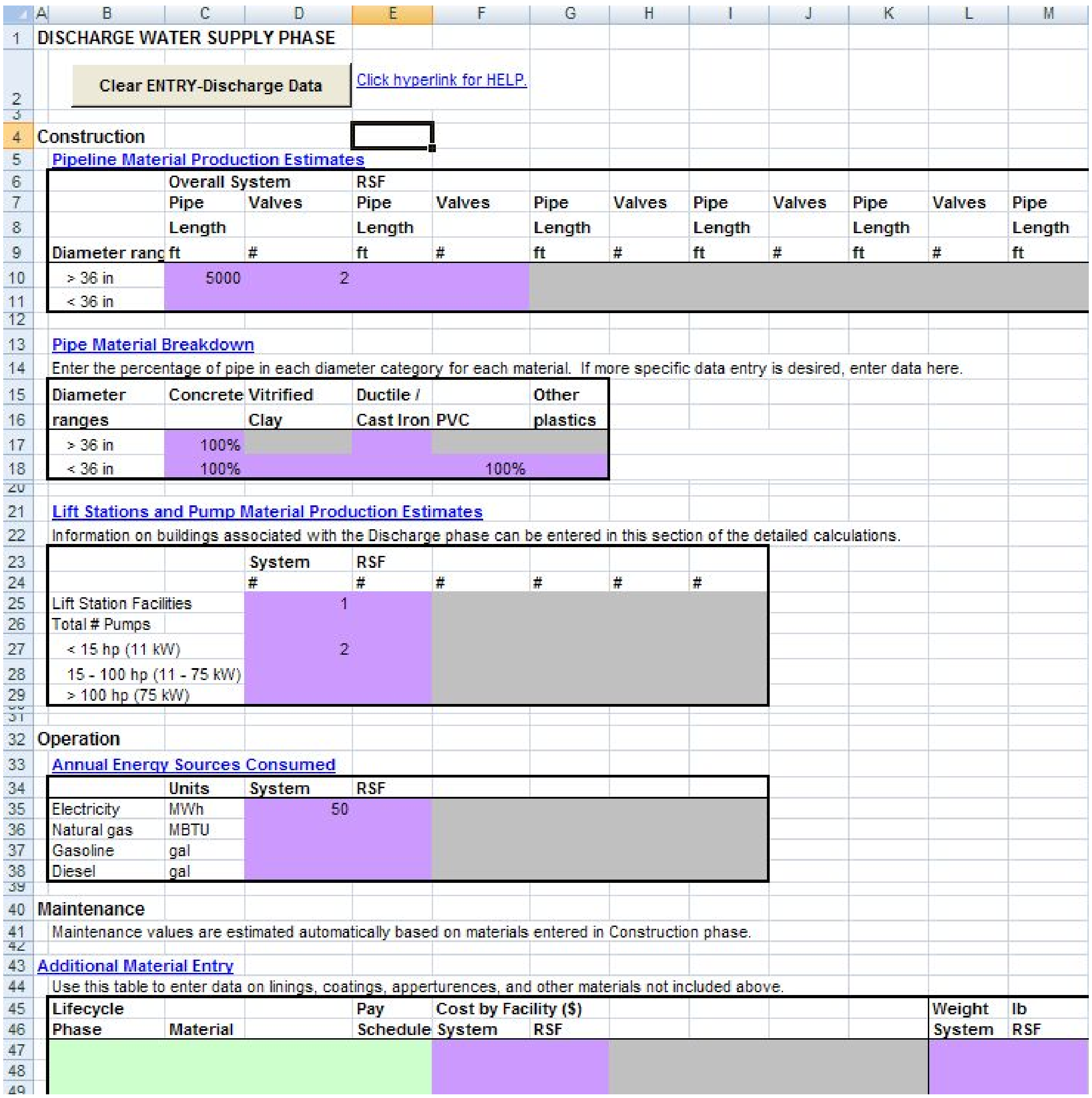

Figure 4: ***Entry- Discharge*** **Worksheet**

Manholes. (Collection only.)

- TYPE: The user should select the type of manhole, precast concrete or cast-in-place.
- DEPTH: Select the appropriate depth from the drop-down menu.
- INNER DIAMETER: Select the appropriate diameter from the drop-down menu.

For each manhole category, enter the number of manholes needed for the overall system and for each of the WWTPs.

Curb Inlets. (Collection only) For each curb inlet category, enter the number of curb inlets needed for the overall system and for each of the WWTPs.

Lift Station and Pump Material Production Estimates. For the overall system and for each of the WWTPs, the user can enter the number of lift station facilities (i.e., buildings or foundational pads) and the total number of pumps in each of three size categories.

Operational data for Collection and Discharge consists only of energy use. Data for energy use are discussed below:

Annual Energy Sources. For the overall system and for each of the WWTPs, the user should enter annual electricity, natural gas, gasoline, and diesel use.

Additional Material Entry. This table should be used to enter data on materials not included above (e.g., linings, coatings, and apperturences).

- LIFECYCLE PHASE: The user should select the appropriate life-cycle phase construction, operation, and maintenance) from the drop-down menu for each material. Life-cycle phases are defined in Table 1.
- MATERIAL: Select a material from the drop-down menu. A list of materials included in WWEST as well as default service lives and delivery distances are shown in Table 1. Custom materials can be added to WWEST if the user has LCA inventory data for energy use and emissions.
- PAY SCHEDULE: Select the appropriate pay schedule from the drop-down menu. The choices are: one time, once per service life, or annually. If you have entered a cost/weight that will only be used once in analysis period, select one time. If you have entered a cost/weight for single purchase of a material that will be replaced over the analysis period (i.e., filter materials, pumps), enter once per service life. If the material is consumable and will be purchased every year, enter annually.
- COST BY FACILITY: For system and each facility, enter the cost for the material on a one time basis. If the pay schedule is one time or once per service life, enter the cost for the initial purchase. If the pay schedule is annual, enter the annual cost. Enter the total cost for equipment of that type, not the unit cost.
- CARGO WEIGHT: For system and each facility, enter the estimated weight of the material.

Additional Equipment Use. This table should be used to enter data on equipment use not captured elsewhere in the calculations. The equipment needed to construct infrastructure and install equipment described above will be automatically calculated.

- LIFECYCLE PHASE: See Material Entry description.
- EQUIPMENT: Select equipment from the drop-down menu. The equipment options are listed on the "Assump-Equip" worksheet.
- USE SCHEDULE: Select the appropriate use schedule from the drop-down menu (one time, or annually).
- UNITS: The units will be entered automatically. For off-road equipment, the unit is hours. For on-road equipment, the unit is distance.
- USE: For system and each facility, enter the use for each facility. If the use schedule is annually, enter the use for a specific or average year. If it is one time, enter the total equipment use needed for the one time project.

The user can reset default data and clear data entry by clicking the button at the top of the page. Click the "Enter Collection/Discharge Data" button after changes are made to make necessary revisions to future calculations.

7.1.4. COLLECTION and DISCHARGE Assumptions

Additional data about the Collection and Discharge systems can be entered if desired on the "Assump-COL/DIS" worksheet. The user can reset default data and clear data entry by clicking the button at the top of the page.

Pipe Assumptions. For each of the categories of pipe, enter an average pipe depth. This value will be used to estimate equipment use necessary to install the pipelines. Also, the material production costs associated with pipe fittings (e.g., wyes, tees, elbows) are estimate based on the total pipe length in each category. The user can define the average frequency of fittings in the system. The default value is every 200 ft for the Collection system and every 500 ft for the Discharge system.

Pump and Lift Station Assumptions. The table allows the user to refine data for pump station facilities (i.e., buildings, pads, or underground vaults) for the system and each WWTP.

- AVERAGE AREA PER STATION: Enter the average area for each station in the category.
- WALL HEIGHT: Enter the average wall height for each pump station in the category. If the pumps are on pads, the wall height will be zero.
- ABOVE OR BELOW GROUND: The user can select from the drop-down menu whether the pump station is above or below ground. If the user selects average, the average facility is assumed to be partially buried. The selection affects the construction materials and equipment used needed to construct the pump station.
- NUMBER OF STATIONS: Enter the number of stations to which the above average data applies.

The user can enter additional types of pump station for either the system or the WWTPs in the lower half of the table. The user can group and separately enter data for pumps stations housed in buildings and those located just on pads or can enter above and below ground facilities separately.

Click the “Enter Collection/Discharge Assumption Data” button after changes are made to make necessary revisions to future calculations.

7.1.1. TREATMENT Entry

The treatment system entry pages (Entry-TRT) allows the user to define processes in the treatment process, equipment, and information on sludge disposal and energy use lift stations and pumps, and energy consumption. Two assumption pages for treatment (Assump-LTRT and Assump-STRT) allow the user to define information on liquid and sludge treatment, respectively. All information on the Treatment entry pages must be assigned to a specific WWTP. No data can be assigned to the overall system on these pages. The user can reset default assumptions and clear all user data by clicking on the button at the top of the worksheet.

Figure 5 shows a partial view of the Entry-TRT worksheet, focusing on the Process Selection table. The entire table is not shown. The user should enter an “X” for each treatment process present in a particular WWTP. The selections, combined with the population served by the WWTP, are used to establish the default infrastructure size and material use.

In-plant Piping and Material Production Estimates. The user can enter information on pipes, valves, and flowmeters within the plant. Entry in this table is optional. If the table is left blank, WWEST will use a standard cost estimate for water system to determine piping costs. The assumption is that piping costs are equal to 8 percent of total equipment costs.

Pump Material Production Estimates. The user can enter the number of pumps in three categories for all the treatment plants. Pumps are divided between liquid and sludge treatment and are categorized by power and by function. Chemical metering pumps are in a separate category.

Reset Default Treatment Data | Click hyperlinks for HELP.

Enter an "X" next to the components of each treatment process. Grayed out cells are not available for entry because of a user selection.

Plant Summary	Units	RSF
Average influent raw sewage volume	MGD	50
Influent BOD5 content	mg/L	300
Influent Total N	mg/L	
Influent Total P	mg/L	
Total N in sludge		
Total P in sludge	mg/kg	
BOD content in		
Liquid Treatment Process Selection		
Primary treatment (septic tanks)		
Screening		
Coarse screening (0.24-5.9 in, 6-150 mm)		
Medium / Fine screening (<0.23 in, <6 mm)		x
Grinding (macerator/comminutor)		
Grit chamber		
Flow equalization basin		X
Rapid Mix Basin		
Coagulation/Flocculation		
Sedimentation/Clarification		
Filtration		
Conventional filtration		X
Membrane filtration		
Activated sludge (AS)		
Conventional continuous flow AS		x
Extended aeration continuous flow A		
Sequencing batch reactors AS		
Ponds/Lagoons		
Facultative ponds		
Anaerobic ponds		
Facultative aerated lagoons		
Sedimentation ponds		
Completely mixed aerated lagoons		
Maturation ponds		
Membrane bioreactors		
Carbon adsorption		
Disinfection		X
Sludge Treatment Process Selection		**RSF**
Sludge grinding/screening		x
Storage tanks		x
Thickening/dewatering		
Sludge drying bed		
Belt press		
Centrifuge		x
Thermal drying		
Filter press		
Gravity thickening		
Belt filter press		
Sludge lagoons		
Vacuum filter		
Digestion stabilization		x

Figure 5: *Entry-TRT* Worksheet- Process Selection Table

Figure 6 shows another partial view of the Entry-TRT that focuses on operational effects, including energy, sludge, and direct emissions.

Operation

Annual Energy Sources Consumed

	Units	RSF
Liquid Treatment		
Electricity	MWh	17
Natural Gas	MMBTU	
Gasoline	gal	
Diesel	gal	
Solids Treatment		
Electricity	MWh	
Natural Gas	MMBTU	
Gasoline	gal	
Diesel	gal	

Annual Energy Recovery

	Units	RSF
Liquid Treatment		
Electricity	MWh	
Solids Treatment		
Electricity	MWh	

Disposal electricity generation information (e.g., landfi
based on data from Assump-STRT worksheet.

Note: Default electricity estimates (based on Von Sperling 2005) include electricity associated with AERATION primarily and are provided as guidar

Annual Chemical Consumed

	General		RSF							
		Chemical	Chemical	Delivery	Storage	Tank	Chemical	Delivery	Storage	Tank
	Cost	Density	Volume	Distance	Tanks	Size	Volume	Distance	Tanks	Size
Chemical	$/gal	lb/gal	gal	mi	#	gal	gal	mi	#	gal
LIQUID TREATMENT										
SOLIDS TREATMENT			RSF							

Annual Sludge Production

	Units	RSF
Primary Sludge	cy/yr	
Secondary/Tertiary Sludge	cy/yr	
Sludge to be treated (wet)	cy/yr	
Sludge to be treated (dry)	cy/yr	40
Sludge to be disposed (wet)	cy/yr	

Annual Greenhouse Gas Emissions Production

% CH4 captured (see note)	Units	RSF
Liquid Treatment		
Centralized aerobic treatment	%	
Anaerobic reactor	%	
Anaerobic lagoon	%	
Septic system	%	
Sludge Treatment		
Anaerobic digester	%	
Disposal	%	
Landfill	%	
Composting	%	
Incineration	%	

Figure 6: *Entry-TRT* Worksheet- Operational Data Table

Annual Energy Sources. For the liquid and sludge processing systems for each of the WWTPs, the user should enter annual electricity, natural gas, gasoline, and diesel use.

Annual Energy Sources and Recovery. In the left-hand table, the user should enter annual electricity, natural gas, gasoline, and diesel use for the liquid and sludge processing systems for each of the WWTPs. The user should enter the total electricity use, whether generated on-site or off-site. The right table can be used to provide information on electricity generated on-site as part of an energy recovery system.

Annual Chemical Consumed. This table allows the user to enter data about the chemicals used in both the liquid and sludge treatment systems.

- CHEMICAL: Select the chemical from the drop-down menu. If a chemical is not present, the user can select the closest approximation, enter it into the “Additional Material Entry” table with a general category (e.g., other basic inorganic industrial chemicals), or add a chemical by defining it as a custom material on the “Assump-General” worksheet and click the “Enter General Assumptions data” button. Also add it to the chemical list on the “Conv” worksheet (in the Background data) in cells F43 to F48.
- GENERAL COST: Unless the cell is shaded grey, enter the unit cost for the chemical.
- CHEMICAL DENSITY: Enter the chemical density.

For each WWTP, enter the chemical volume, the delivery distance from the manufacturer, the number of storage tanks needed on-site, and the average size of those storage tanks.

Annual Sludge Production. This table allows the user to enter data about the sludge produced in the treatment systems. Default values if present, should be checked and refined by the user.

Annual GHG Emissions Capture. This table allows the user to define the capture rate for methane for the system. The capture rate is used to refine the default GHG calculations. The user can also opt to ignore the capture rate entry and instead just refine the GHG emissions on the “Assump-LTRT” and “Assump-STRT” worksheets.

Additional Material Entry. This table should be used to enter data on materials not included above (e.g., linings, coatings, and apperturences). See the instructions in Section 6.1.3.

Operational Equipment Use. This table should be used to enter data on equipment use not captured elsewhere in the calculations. The equipment needed to construct infrastructure and install equipment defined above will be automatically calculated. See the instructions in Section 6.1.3.

The user can reset default data and clear data entry by clicking the button at the top of the page. Click the “Enter Treatment Data” button after changes are made to make necessary revisions to future calculations.

7.1.1. Assumptions-Liquid Treatment Worksheet

The assumption page for liquid treatment (Assump-LTRT) allows the user to define information on liquid treatment. All information on the Treatment entry pages must be assigned to a specific WWTP. No data can be assigned to the overall system on these pages. The user can reset default assumptions and clear all user data by clicking on the button at the top of the worksheet.

In the General Assumptions section,

Process Tank Wall Thickness. This table allows the user to enter data about the wall thickness for steel and cast-in-place tanks used in the system. These are used to estimate the material use for infrastructure construction.

Population Table. This table allows the user to define the number of people served by each WWTP. Most default values for treatment processes are based on per capita values. The default values distribute the service area population proportionally by plant production. The user can refine these as needed.

If General Assumptions have been changed, click the button below to update the calculations based on the revised inputs.

GHG Emission Calculations Table. The default values in this table are based on Assumptions from (IPCC 2006). The user can revise the values as needed. If default values aren't shown, be sure the "Enter General Liquid Assumptions" button has been clicked.

The following section allows the user to enter detailed process assumptions for various treatment processes. Default values may be available for some processes, though not all. Figure 7 shows a partial view of the detailed treatment process entry page. The data need varies widely for each process but some are consistently used and are described here in an overview section.

- TREATMENT TRAINS (#): The user should enter the number of treatment trains (i.e., process streams) associated with this treatment process.
- PLANT ID: The WWTP identification for all named plants will appear automatically. If fewer than 5 plants are used, some cells will be grayed out. In some cases, there are cells at the bottom of the table for the user to enter multiple criteria for the process at the same plant by selecting the plant id from the drop-down menu.
- TANKS or EQUIPMENT (#): The user should enter the number of tanks or pieces of equipment used for this treatment process. In some cases, the entry table will specify that the user should enter the number per treatment train. The user should be attentive to the units required.
- TANK MATERIAL: The user should select the appropriate tank material from the drop-down menu. The choices generally include concrete and steel.
- DIMENSIONS: Enter the dimensions (depth [D], width [W], length [L], area, and/or diameter [Dia]).
- COST: Enter the cost for the specified process equipment. The user should pay attention to the required units which may be the total cost for the process, the cost per treatment train, or the cost per unit.
- EQUIMENT/MATERIAL SERVICE LIFE: Enter the number of years that the average unit is expected to last before replacement is needed.

More specific details about data entry in this for specific processes are listed below.

Activated Sludge

Assumes a square reactor. If reactor is not square, please estimate the equivalent dimensions for a square reactor.

		Activated Sludge Reactor Data				Nutrient Removal Data						
Plant ID	AS Type	Treatment Trains #	Depth ft	Side length ft	AS Equip Costs $/train	N removal	P removal	Nut.Rem. Tanks #	Depth ft	Side length ft	N/P Rem. Equip. $/train	Other Equip Costs total $
RSF												

Note: AS equipment includes aeration and recirculation equipment.

Ponds/Lagoons

Default values are only available for the first pond type selected. If multiple pond types are present, other data must be entered by the user.

	PONDS 1			Dimensions						PONDS 2		
Plant ID	Pond Type		Ponds #	D ft	W ft	L ft	Liner Cost $/pond	Biogas Cover $/pond	Equip Cost $/pond	Pond Type		Ponds #
RSF												

Membrane bioreactors

Plant ID	MBR type	Aerobic/ anaerobic	Config- uration	Membrane Material	Treatment Trains #	Basin Dimensions D ft	W ft	L ft	Cartridges per train #	MBR Cost $/cartridge	Cartidge avg life years	Blowers cost #/basin
RSF	Aeration MBR	Aerobic	Sidestream	PVDF	4	8	20	30	10	5000	10	5000

Carbon adsorption

No default values are available.

Plant ID	Carbon Type	Treatment Trains #	Carbon Vessels per train #	Tank Volume gal	Carbon Weight lb/vessel	Carbon average life years	Equip. Cost $/train
RSF							

Figure 7: *Assump-LTRT* Worksheet- Detailed Process Data

Septic Tank Table.

- COMPARTMENTS: Select whether the septic tank is a single or double compartment tank.
- CLEANING FREQUENCY: Enter the average number of years between pumping sludge out the septic tank.

Screening Table. Select the TECHNOLOGY TYPE for the screen from the drop down menu (fixed incline screen, rotary drum, horizontal reciprocating, tangential).

Grinding Table. Select the TECHNOLOGY TYPE for the screen from the drop down menu (grinder, macerator, and comminutor).

Grit Removal Table. Select the TECHNOLOGY TYPE for the screen from the drop down menu (horizontal flow, aerated, and vortex).

Flow Equalization/Storage Table.

- TOTAL STORAGE CAPACITY: Enter the volume of each storage basin. If multiple storage basins, they can be entered separately or can be entered based on the average capacity and dimensions.
- MIXED/BAFFLED: Select whether a mechanical mixer or static baffles are present in the tank.
- AERATED: Select whether this feature is present for the storage basins.

Coagulation/Flocculation Table. In the MIXED/BAFFLED column, select whether a mechanical mixer or static baffles are present in the tank from the drop down menu.

Sedimentation/Clarification Table.

- TREATMENT STAGE: Select whether the process is part of primary or secondary treatment.
- TREATMENT OPTIONS: Select the appropriate treatment option, if needed (high rate, waste activated sludge return, flocculation/sedimentation, or stacked tanks).
- TANK SHAPE: Select the tank shape from the drop-down menu (rectangular or circular).

Conventional (Depth) Filtration Table.

- MEDIUM DEPTH: Enter the depth of all filter media in the appropriate columns.
- TANK SHAPE: Select the tank shape from the drop-down menu (rectangular or circular).

Membrane Filtration Table.

- MEMBRANE TYPE: Select the membrane type from the drop-down menu (microfiltration, ultrafiltration, nanofiltration, and reverse osmosis).
- MEMBRANE MATERIAL: Select the material from the drop-down menu (PPE, cellulose acetate, polyamides, thin film cellulose).
- MEMBRANE WEIGHT: Enter the average weight per membrane unit; used to calculate material delivery effects.

Activated Sludge Table.

- ACTIVATED SLUDGE TYPE: The process type will be automatically entered based on input from the ENTRY-TRT page.
- NUTRIENT REMOVAL (Nitrogen and Phosphorous): Enter whether nutrient removal processes are present (yes/no).

Ponds/Lagoons Table.

- PONDS TYPE: The first pond type will be entered automatically based on input from the ENTRY-TRT page. If a second type of pond, it should be selected from the drop-down menu in Column M.
- LINER/BIOGAS COVER COST: Enter the costs for liners and biogas covers, if present. Both are assumed to be made of plastic material.

Membrane Bioractors (MBR) Table.

- MBR TYPE: Select either separation, aeration, and extraction MBR from the drop-down menu.
- AEROBIC/ANAEROBIC: Select aerobic or anaerobic from the drop-down menu.
- CONFIGURATION: Select submerged or sidestream from the drop-down menu.
- MEMBRANE MATERIAL: Select the material from the drop-down menu (PVDF, polyamides, thin film cellulose, etc.).

Carbon adsorption Table.

- CARBON TYPE: Select granular or powdered activated carbon from the drop-down menu.
- TANK VOLUME: Enter the volume of the carbon vessel.
- CARBON WEIGHT: Enter the weight of the carbon material per vessel.

Chlorine-based Disinfection Table.

- CHLORINE USED?: Select yes from the box if a chlorine based disinfection method is used.
- CHEMICAL TYPE: Select the chlorine chemical from the drop-down menu (chlorine, gas or compressed, chloramines, sodium hypochlorite, chlorine dioxide)
- DECHLORINATION? Select yes if a dechlorination process is present. Basin dimensions for dechloriniation process should be entered separately.

Ozone Disinfection Table.

- OZONE USED?: Select yes from the box if an ozone-based disinfection method is used.
- DOSE: Enter the average dose of ozone in mg/l.

Ultraviolet (UV) Disinfection Table.

- UV USED?: Select yes from the box if an UV-based disinfection method is used.
- DOSE: Enter the average dose of ozone in mJ/cm^2.

The user can reset default data and clear data entry by clicking the button at the top of the page. This will delete all user-entered data in the sheet. Click the “Enter Liquid Treatment Assumptions” button after changes are made to make necessary revisions to future calculations.

7.1.2. Assumptions-Sludge Treatment Worksheet

The assumption page for liquid treatment (Assump-STRT) allows the user to define information on sludge treatment. All information on the Treatment entry pages must be assigned to a specific WWTP. No data can be assigned to the overall system on these pages. The user can reset default assumptions and clear all user data by clicking on the button at the top of the worksheet. The sheet is similar to the “Assump-LTRT” page in structure.

GHG Emission Calculations Table. The default values in this table are based on Assumptions from (IPCC 2006). The user can revise the values as needed. If default values aren’t shown, be sure the “Enter General Liquid Assumptions” button on the “Assump-LTRT” sheet been clicked.

The following section allows the user to enter detailed process assumptions for various treatment processes. Default values may be available for some processes, though not all. Figure 7 shows a partial view of the detailed treatment process entry page. The data need varies widely for each process but some are consistently used. These are listed here and are described here in the previous section on Liquid Treatment.

- PLANT ID
- TREATMENT TRAINS (#)
- TANKS or EQUIPMENT (#)
- TANK MATERIAL
- DIMENSIONS
- COST:
- EQUIMENT/MATERIAL SERVICE LIFE

More specific details about data entry in this for specific processes are listed below. Grinding and flow equalizations/storage are previously described in the Liquid Treatment section above.

Mechanical Thickening/Dewatering Table.

- EQUIPMENT TYPE: Select the appropriate equipment from the drop-down menu (centrifuge, filter press, belt press, vacuum filter)
- HOURS OF USE: Enter the average hours of use for the equipment per day.

Gravity Thickening/Dewatering Table. Select the technology type from the drop-down menu (gravity or dissolved air).

Ponds Thickening/Dewatering Table.

- BED TYPE: The bed type should be selected from the drop-down menu (conventional sand bed, paved bed, reed bed, lagoon).
- BED FOUNDATION AND WALLS MATERIALS: Select either concrete, earthen, or asphalt from the menu.
- CLEANING METHOD: Select the cleaning method from the drop-down menu (manual or mechanical).
- MIXING?: Select whether mixing is present.

Digestion Table. Select the technology type from the drop-down menu (conventional aerobic, pure oxygen, thermophilic, and anaerobic).

DISPOSAL

Two entries are common to all disposal methods:

- SOLIDS DISPOSAL: Enter the percentage of solids disposed in each manner.
- DISTANCE: Enter the distance to the specified disposal site.

Land Application

- FERTILIZER OFFSET: Select yes or no to indicate whether the land-applied solids are used to offset commercial fertilizer production.
- APPLICATION METHOD: Select whether the solids are applied wet or dry.
- APPLICATION RATE: Enter the rate of application in mass per area units.
- STORAGE PERIOD: Enter the period (in weeks) when sludge must be stored prior to land application.

Landfill

- GAS RECOVERY: Select yes or no to indicate whether the landfill recovers methane gas.
- GAS TREATMENT: Select the means of treating captured gas at the landfill (flare, generate electricity).

Incineration

- INCINERATOR TYPE: Select multiple hearth or fluidized bed-type incinerator.
- APPLICATION METHOD: Select whether the solids are applied wet or dry.
- ASH DISPOSAL SITE: Select the means of disposal of the ash, an incineration by-product (ash lagoon, landfill, industrial use).

Disposal EF Table: The user can edit the emission factors for various disposal options if more applicable values are available. Default values are discussed on the "Disposal" worksheet in the background section.

7.2. Results Worksheets

Several results worksheets are available. Results are reported in terms of functional unit (i.e., per volume of wastewater treated) and are shown numerically on all sheet. A summary worksheet of graphical results is also available. Results are also given for the cumulative wasteater system and for each independent WWTP

A summary page, seen in Figure 8, provides total results for all activities. Results pages for each separate activity are also available with a similar format. The user can customize results pages to show additional results as desired.

Key to Abbreviations

Units		Facility		Wastewater Phase	
Mg	Million grams	Sys	System	Col	Collection
MJ	Megajoules	1	RSF	LT	Liquid treatment
Contaminants		2		ST	Solid treatment
CO_2 eq.	Carbon dioxide equivalents	3		DIS	Discharge
		4			
NO_x	Nitrogen oxides	5			
PM	Particulate matter	**Life-cycle Phase**		**Activity**	
SO_x	Sulfur oxides	CON	Construction	MP	Material production
VOC	Volatile organic compound	OP	Operation	MD	Material delivery
NMVOC	Non-methane volatile organic compound	MNT	Maintenance	EU	Equipment use
CO	Carbon monoxide	EOL	End-of-life / Disposal	EP	Energy production
HC	Hydrocarbons			Disp	Disposal

TABLE 1: Summary Results

Chem-ical	Total	Weighted Total	Facility SYS	1	2	3	4	5
Results per functional unit (MJ for energy, Mg for other)								
Energy	2E+05	2E+05	1E+05	7E+04	0E+00	0E+00	0E+00	0E+00
CO_2 eq.	9E+00	9E+00	6.8E+00	2E+00	0.0E+00	0E+00	0E+00	0E+00
NO_x	2E-02	2E-02	2E-02	2E-03	0E+00	0E+00	0E+00	0E+00
PM	2E-02	2E-02	1E-02	1E-03	0.0E+00	0E+00	0E+00	0E+00
SO_x	1E-02	1E-02	1E-02	1E-03	0E+00	0E+00	0E+00	0E+00
VOC	1E-02	1E-02	1E-02	8E-04	0E+00	0E+00	0E+00	0E+00
CO	5E-02	5E-02	5E-02	5E-03	0E+00	0E+00	0E+00	0E+00
Results (% of total)								
Energy	--		57%	43%	0%	0%	0%	0%
CO_2 eq.	--		77%	23%	0%	0%	0%	0%
NO_x	--		92%	8%	0%	0%	0%	0%
PM	--		91%	9%	0%	0%	0%	0%
SO_x	--		91%	9%	0%	0%	0%	0%
VOC	--		92%	8%	0%	0%	0%	0%
CO	--		91%	9%	0%	0%	0%	0%

Averages of all plants- system and non-system results

Chem-ical	Water Supply Phase Col	LT	ST	DIS	Life-cycle Phase CON	OP	MNT	EOL	Activity MP	MD	EU	EP	Disp	Direct
	Functional unit =			1.0E+00	MG									
Energy	7.6E+04	7.3E+04	1.2E+03	2.1E+04	1E+05	2E+04	4E+04	0E+00	1E+05	1E+04	7E+03	2E+04	0E+00	
CO_2 eq.	5.6E+00	1.5E+00	5.5E-01	1.1E+00	6E+00	2E+00	4E-01	0E+00	6E+00	4E-01	5E-01	9E-01	0E+00	1E+00
NO_x	2E-02	2E-03	8E-05	2E-03	2E-02	1E-03	9E-04	0E+00	1E-02	5E-03	3E-03	1E-03	0E+00	
PM	1E-02	1E-03	2E-04	2E-03	1E-02	3E-03	9E-04	0E+00	1E-02	6E-04	5E-04	3E-03	0E+00	
SO_x	1E-02	1E-03	3E-05	2E-03	1E-02	4E-04	8E-04	0E+00	1E-02	4E-04	1E-03	4E-04	0E+00	
VOC	9E-03	8E-04	5E-05	9E-04	9E-03	6E-04	5E-04	0E+00	8E-03	1E-03	4E-04	7E-04	0E+00	
CO	4E-02	5E-03	4E-05	2E-03	5E-02	6E-04	4E-03	0E+00	5E-02	2E-03	1E-03	6E-04	0E+00	
Energy	45%	43%	1%	12%	66%	9%	25%	0%	79%	7%	4%	9%	0%	
CO_2 eq.	64%	17%	6%	13%	72%	24%	5%	0%	65%	4%	6%	10%	0%	15%
NO_x	82%	8%	0%	10%	91%	5%	4%	0%	57%	23%	15%	6%	0%	
PM	79%	8%	1%	12%	77%	18%	6%	0%	75%	4%	3%	18%	0%	
SO_x	80%	8%	0%	11%	92%	2%	6%	0%	88%	3%	7%	3%	0%	
VOC	84%	7%	0%	9%	89%	6%	5%	0%	76%	14%	3%	7%	0%	
CO	86%	9%	0%	5%	91%	1%	8%	0%	92%	4%	3%	1%	0%	

Figure 8: Summary Results

7.3. Calculations Worksheets

Calculation worksheets are present for each of the activities described in the Entry section. These worksheets are locked so that users can not inadvertently change an equation.

7.4. Explanatory Worksheets

Hyperlinks are present throughout the tool that link to explanations of the cell contents and equations used. These worksheets provide similar content as this user manual but are more detailed. The explanatory (EXP) worksheets include:

- Update Log: Provides a list of revisions made to the WWEST tool since its original release.
- HELP-General: Provides guidance for cell formatting, summarizes acronyms and abbreviations, and defines life-cycle phases, wastewater phases, facilities and activities. It also lists general calculations used throughout the tool.
- HELP-Entry: Lists guidance for each column or cell in the Entry worksheets.
- HELP-Calcs: Provides specific details about WWEST calculations.
- HELP-Results: Summarizes information about the Results worksheets.
- HELP-Refs: Lists references used in the WWEST tool.

7.5. Data Worksheets

Background worksheets are present with data necessary to complete the LCA calculations. These worksheets are locked so that users can not inadvertently change data. The following are the names and brief descriptions of the data worksheets:

- Lists includes the list and default assumptions about material choices, ENR's Construction Cost Index data for discounting, and terms for certain drop-down mists.
- Final air EFs: Summarizes EFs for air emissions from EIO-LCA and other sources.
- Final water EFs: Lists EFs for water emissions.
- Cost Assumptions (Assump): Includes construction parameters, unit weights, and unit costs for basic materials.
- MD EFs Includes EFs for transport vehicles (truck, train, ship, plane).
- EU Data: contains default data on construction equipment productivity and pipe parameters.
- Equipment use (EU) impacts: Contains EFs for some non-road diesel and gasoline equipment and direct electricity EFs.
- Electricity (Elect) EFs: Provides estimates of direct and life-cycle fuel-specific electricity EFs and state and national averages.
- Disposal: Lists EFs for disposal options.
- Conversions (Conv): Includes unit conversions, material densities, heat contents, global warming potentials of GHGs, and similar data.
- Climate Change (CC) regulation (reg) data: provides EFs and data on the California climate change rules.
- LTRT data: Contains default data for liquid treatment processing equipment.
- STRT data: Contains default data for solids treatment processing equipment.
- Fertilizer (Frtlzr) data: Lists assumptions used to calculate fertilizer offsets for land application of sludge.
- Fuel EFs: Describes EFs for fuel production for a variety of fuels including gasoline, diesel, ethanol, biodiesel, and fuel cells.

8.0 Where else can I learn about WWEST?

Additional information on this research can be found in the following publications:

- Stokes, J. Life-cycle Assessment of Alternative Water Supply Systems in California. Unpublished Ph.D. dissertation. University of California, Berkeley, California. May 2004.
- Stokes, J. R. and A. Horvath (2009). "Energy and Air Emission Effects of Water Supply." Environmental Science & Technology **43**(8): 2680-2687.

The final report for the California Energy Commission project completed between 2006 and 2010, including the tool described herein, should be available on the Energy Commission website in early 2011.

9.0 Acknowledgments

Funding for WWEST has been provided by the California Energy Commission Public-Interest Energy Research (PIER) program.

10.0 Frequently Asked Questions (FAQs)

How can I obtain the tool and learn about changes to the tool and the user's guide?

WWEST users should request a copy of the tool and companion documentation by registering with the tool authors by sending an email to UCBWaterLCA at gmail dot com with following information:

- Name
- Email
- Phone and fax number
- Employer, school, or other affiliation
- The tool you are interesting in (WWEST, WWESTCalc, WWWEST)
- Purpose for using the tool

Registered users will be notified of updates to the tool and to the user's manual when they become available. Both the tool and the documentation will be updated as project constraints allow.

I do not agree with default assumptions present in WWEST. How can I suggest changes?

Most assumptions in WWEST can be changed by the user in the tool. In some cases, a cell may need to be unlocked prior to the change.

In addition, the tool creators are always interested in improving WWEST by including better default assumptions about, for example, material service lives, delivery distances, equipment and material costs, and EFs. Please send your suggestions to the tool developers at UCBWaterLCA at gmail dot com so they can be included in future tool versions.

How can I change the values in a locked cell?

On data entry and results pages, the password needed to unlock cells is "WEST." A different password is used for calculation and background pages. The tool developers do not encourage changes to these pages. If the user wishes to change cells on these worksheets, please contact the tool developers at UCBWaterLCA at gmail dot com to obtain the password.

I am getting an error message in the results (#REF or #NAME, etc,). What can I do to resolve this?

First, a tip: DO NOT SORT data that has been entered in the tool OR DELETE lines out of the entry tables. This will cause errors in the calculations. Also, make sure that all “Enter data” buttons have been clicked in succession before results are finalized.

If that does not resolve the problem, review the phase specific results (i.e., Results- COL, Results- LTRT) pages to see which calculations are causing the error. If the error is occurring in many cells on all pages, the error is likely to be related to the basic data entry on the Entry-General Info page. A required entry may have been left blank in the Facilities table, for example. If the omission is not obvious, follow the instructions for more specific errors.

If only one cell or a few cells are showing error messages, go to the corresponding Calcs page and try to identify which input is causing the error. Scroll down through the calcs to find where it is occurring. When it is located, highlight a cell with the error message. If you highlight portions of the formula and hit F9 you can identify what the value is being assigned to each term in the formula.

11.0 References

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Appendix A.2.2:
WWEST Revision Logs

Summary of Revisions to WWEST

Revised: 6/29/2010

Prior CEC Task

Date	Description of Change
7/1/2010	- Corrected error to Results- Summary worksheet that double-counted treatment effects
6/29/2010	- Added the capability to assess membrane bioreactors
6/21/2010	- Corrected calculation errors based on case study analysis
5/20/2010	- Added the capability to analyze septic tanks and ultraviolet disinfection
5/14/2010	- Updated macros to allow sheets to be protected/unprotected during operation - Added fiberglass tanks to the list of materials
3/19/2010	- Updated references for new emissions factors in WWEST
3/12/2010	- Inserted new emission factors for fuel production from GREET model (2010) - Edited fuel production calculations to include alternate fuels in final results
3/9/2010	- Calculated fuel consumption values for delivery modes for Efs from OECD source to provide more complete analysis of these modes - Updated Material delivery calculations as needed to incorporate new emission factors from Facanha and Horvath 2007
3/8/2010	- Added passenger transit modes emission factors from Chester 2008 to the 'EU Efs' worksheet. These can be used as custom equipment on the Assump-Equip worksheet.
3/5/2010	- Updated material delivery emission factors with data from Facanha and Horvath's 2007 paper, simplified airplane and edited summary material delivery calculations to correct errors for specific delivery modes
3/4/2010	- Updated electricity Efs with 2005 state data from E-GRID
3/1/2010	- Updated electricity life-cycle emission factors so that they are as specific as possible to Western climate and most common fuel sources (i.e., PV park solar and large reservoir-based hydropower)
1/14/2010	- Updated equipment use calcs to correct an error in the functional unit calculations
12/1/2008	- WWEST tool released at the completion of Task 10

Appendix A.2.3:
WWEST Help Pages

HELP- GENERAL

Jump to Topic:

Cell Formatting Key
Acronyms and Abbreviations
Worksheet Type Definitions
Analysis Alternatives Definitions
Wastewater Phase
Lifecycle Phase
Facilities
Activities
General Equations for Activities
General Terms
Material Production
Material Delivery
Equipment Use
Energy Production
Direct Emissions
Sludge Disposal
Recommended Data Entry Order
Developer Contact Information

CELL FORMATTING KEY

(green)	Drop-down Menu
(purple)	Data required from user
(yellow)	Cells with assumptions or data which can be checked by the user
(orange)	Cells containing calculations

ACRONYMS AND ABBREVIATIONS

AS	Activated Sludge
Avg	Average
C or Con	Construction
cf	Cubic feet
cm	Centimeters
CO	Carbon monoxide
CO_2eq	Carbon dioxide equivalents
Col	Collection
Conv.	Conventional
D	Depth
d	Day
Dia.	Diameter
Dim.	Dimensions
Dis	Discharge
Efs	Emission factors
EOL	End-of-life
EP	Energy production
equip.	Equipment
EU	Equipment use
Ext. Aer.	Extended aeration
ft	Feet
ft2 or ft^2	Square feet
m	Meter
M or MMT	Maintenance
m2 or m^2	Square meters
m3 or m^3	Cubic meters
matl	Material
MD	Material delivery
memb	Membrane
MG	Million gallons
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
MGD	Million gallons per day
mi	Mile
MJ	Megajoules
ML	Million liters
ML/d	Million liters per day
mm	Millimeters
MMBTU	Million BTUs
MP	Material production
mpg	Miles per gallon
MWh	Megawatt-hour
N	Nitrogen
NOx	Nitrogen oxides

ft3 or ft^3	Cubic feet	Nut. Rem.	Nutrient removal
gal	Gallons	O or Op	Operation
gal/h	Gallons per hour	P	Phosphorus
GHG	Greenhouse gas	PM	Particulate matter
GWE	Global warming effect (in units of CO_2eq)	PVC	Polyvinyl chloride
h or hr	Hour	SBR	Sequencing batch reactors
hp	Horsepower	SD	Sludge disposal
in.	Inch	sf	Square feet
inf	Influent	SOx	Sulfur oxides
kg	Kilogram	Sys	System
km	Kilometer	T or Trtmt	Treatment
kW	Kilowatt	VOC	Volatile organic compound
kWh	Kilowatt-hour	W	Width
l	Liter	Wksht	Worksheet
L	Length	WWTP	Wastewater treatment plant
lb	Pound	yr	Year

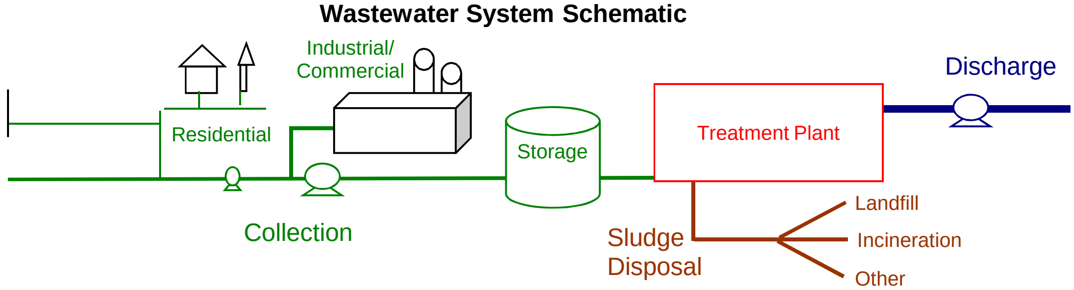
WORKSHEET TYPE DEFINITIONS

Entry	Data entry worksheets are designed to help the user define the basic information necessary for the analysis.
Assump	Assumption entry worksheets may be edited by the user if a more detailed and accurate analysis is desired. The analysis can be conductedif these sheets are left unchanged.
Results	Results worksheets provide the final results both tabularly and graphically. These sheets can not be edited by the user but data can be copied into a separate workbook and manipulated.
DefConv	Default and conversion worksheets store default values for data entry and convert user input into consistent units prior to completing calculations. These worksheets can not be edited by the user.
Calcs	Calculation worksheets show the equations and data manipulation used to determine the final results. These worksheets can not be edited by the user.
Bkgrd	Background data worksheets contain constants and other data used in the tool. These work-sheets can not be edited but can be used as guidance when the user is editing assumptions.

ANALYIS ALTERNATIVE DEFINITIONS

Wastewater Phase (including schematic)

Wastewater System Schematic



Collection: All infrastructure in the processes prior to the WWTP intake point (sewers and lift stations).
Treatment: All infrastructure present at the WWTP facility related to the operation and maintenance of the treatment process.
Discharge: All infrastructure used to carry liquid output from the WWTP effluent point to the outfall.

Life-cycle Phase:

Construction: Analyzing construction includes assessing the life-cycle impacts of producing all materials used in the system (i.e., concrete used in the treatment plant, steel used in pipelines), emissions associated with delivering those materials to the job site, emissions from construction equipment, and producing the fuel/energy used to operate it.

Operation: Analyzing operation includes assessing the life-cycle impacts of producing all chemicals, electricity, and other fuels used in system operation, emissions from the treatment process (e.g., digestion), and emissions from fleet vehicle operations and the impact of producing the fuel to operate the vehicles

Maintenance: Analyzing maintenance includes assessing the life-cycle impacts of producing all materials replaced and enervy expended during expected maintenance (e.g., valves, pumps) and delivering them to the site

Facilities:

System: The System includes all items listed in the System column of the collection and discharge entry worksheets as well as any WWTPs designated as part of the System in the Facility table on the "General Info" worksheet.

WWTPs: The results for each WWTP include only the effects associated with items assigned to that WWTP in data entry tables. Up to 5 WWTPs can be entered. Each one can be designated in

Activities:

Material Production: Material production calculates the energy use and environmental effects associated with manufacturing all material inputs into the infrastructure and operations of the wastewater process (e.g., concrete, pumps, electrical equipment, chemicals, and filter media. The effects are estimated throughout the supply chain.

Material Delivery: Material delivery calculates the energy use and environmental effects associated with transporting material inputs to the infrastructure and operations to the use site by the following modes: local truck, long distance truck, plane, ship, and train. Up to two transportation modes can be entered into the tool.

Equipment Use: Equipment use calculates the energy use and environmental effects associated with operating construction and maintenance equipments, including backhoes, dump trucks, cranes, generators, and other equipment.

Energy Production: Energy production calculates the energy use and environmental effects associated with generating electricity and manufacturing other fuels used in wastewater processing. The electricity emissions calculated can be either direct (smokestack) or indirect (life-cycle, including extracting and processing fuel).

Direct Emissions: Direct emissions calculates the emissions of non-CO_2 greenhouse gases directly from the treatment process (e.g., methane produced in anaerobic reactions).

Sludge Disposal: Sludge disposal calculates the energy use and environmental effects associated with transporting sludge to its permanent disposal site and with the long-term effects of disposal by means of landfill, incinerator, agricultural reuse, and use in industry.

GENERAL EQUATIONS FOR ACTIVITY CALCULATIONS:

General Terms: Equations shown for each activity are for one-time purchase/delivery/use unless noted. The following rules are used to allocate results under other conditions.

Annual: If the purchase/delivery/use is ANNUAL the one-time results are multiplied by the analysis period.

Once per service life: If the purchase/delivery/use is ONCE PER SERVICE LIFE the one-time results are multiplied by the analysis period and divided by the material service life.

Generally, the first purchase/delviery/use of a material is allocated to the CONSTRUCTION phase and is calculated as a one-time purchase.

Maint: Additional purchases (if the service life is shorter than the analysis period) are allocated to the MAINTENANCE phase by multiplying the one-time results by a

Maintenance Factor = (Analysis Pd / Service Life -1).

Subtracting one accounts for the purchase made in the Construction Phase. The maintenance factor is calculated on the DefConv-GI worksheet.

Material Production: When EIO-LCA is the emission factor source for a ONE-TIME purchase:

Emissions (Mg) = EIOLCA EF (Mg/1997$) * Unit Cost (1997$) * Units (#) * Functional Unit (Vol) / Analysis Period (yr) / Volume Treated (Vol/yr)

If costs are entered by the user in units other than 1997$ (as defined on Assump-GEN wkst) a discounting factor based on ENR's Construction Cost Index is included:

Discount = 1997 CCI / Year of Purchase CCI

When a process-based database is the emission factor source for a ONE-TIME purchase:

Emissions (Mg) = Gabi EF (kg/kg) * Unit Weight (kg) * Units (#) * Functional Unit (Vol) / Analysis Period (yr) / Volume Treated (Vol/yr)

Material Delivery: Material delivery calculations for trucks (local and long-distance), ships, and trains are calculated as follows:

Emissions (Mg) = Emisson factor (g/km/kg) * Cargo weight (kg) * Delivery distance (km) * Functional unit (Vol) / Analysis period (yr) / Volume treated (Vol/yr)

Material delivery calculations for planes are calculated as follows:

Emissions (Mg) = (Flight emissions + Landing/takeoff [LTO] emissions) * Functional unit (Vol) / Analysis period (yr) / Volume treated (Vol/yr)

Flight Emissions (Mg) = Flight EF (g/km/kg) * Cargo weight (kg) * Delivery distance (km) * Functional unit (Vol) / Analysis period (yr) / Volume treated (Vol/yr)

Number of trips = Cargo weight (kg) / Frieght capacity (kg) / Trip utilitzation (%)

LTO Emissions (Mg) = LTO EF (g/km/kg) * Cargo weight (kg) * Number of trips * Functional unit (Vol) / Analysis period (yr) / Volume treated (Vol/yr)

Emission factors, frieght capacity and trip utilization are found on the MD EFs worksheet. Cargo weight is based on user entry or unit weights from the Cost Assump worksheet. Delivery distance can be edited on the Assump-GI worksheet; default values are available. Other factors are defined elsewhere.

Equipment Use: Equipment use calculations for NON-ROAD equipment fueled by diesel (backhoes, cranes, etc), gasoline (generators), and electric (saws, etc) are calculated as follows:

Emissions (Mg) = Use (hours) * Emission factor (g/hr) *Functional unit (Vol) / Analysis Period (yr) / Volume treated (Vol/yr) / Equipment or Truck Efficiency (%)

Equipment use calculations for ROAD equipment fueled by diesel (dump trucks, concrete trucks) and gasoline (passenger cars and trucks) are calculated as follows:

Emissions (Mg) = Distance (miles) * Emission factor (mile/hr) *Functional unit (Vol) / Analysis period (yr) / Volume treated (Vol/yr) / Equipment or truck efficiency (%)

The default emission factors for all included equipment types can be edited on the Assump-EQUIP worksheet. Default Efs are found on the DefConv-EQUIP worksheet. Use and distance are calculated based on construction assumptions on the CALC worksheets. Equipment and truck efficiency values are defined and can be edited on the Assump-EQUIP worksheet.

Energy Production: Energy production calculations for electricity are calculated as follows:

Emissions (Mg) = [((Electricity Use - Electricity Recovery [MWh]) *1000 kWh/MWh) + Sum(Electric Equipment Use [Wh] / 1000 Wh/kWh)]* Electricity EF (g/kWh) * * Functional Unit (Vol) / Volume treated (Vol/yr) / 1000000 g/Mg

Electricity use and electricity recovery can be entered on the Entry pages for each phase of the system. Recovery can only be entered for treatment processes. Electricity emission factors can be edited by the user on the Entry-EP page.

Calculations for natural gas energy production are calculated as follows:

Emissions (Mg) = Natural Gas Use (MBTU) * NG EF (g/MBTU) * Functional Unit (Vol) / Volume treated (Vol/yr) / 1000000 g/Mg

Natural gas use can be entered on the Entry pages for each phase of the system. NG Efs can be edited by the user on the Entry-EP page.

Equipment fuel use calculations for each fuel considered (diesel, gasoline) are:

Non-road Equip Fuel Use (gal) = Fuel consumption (gal/hr) * Use (hr) * Functional unit (vol)

/ Analysis Period (yr) / Volume treated (Vol/yr) / Equipment or Truck Efficiency (%)
Road Equip Fuel Use (gal) = Use (mile) / Fuel consumption (mpg) * Functional unit (vol) / Analysis Period (yr) / Volume treated (Vol/yr) / Equipment or Truck Efficiency (%)

Fuel consumption can be edited by the user on Assump-Equip worksheet. Use is calculated as described for the Equipment Use calculations. Other parameters discussed elsewhere.

Material delivery fuel use calculations for each fuel considered (diesel, gasoline, jet fuel) are:
MD Fuel Use (gal) = Distance (km) * Fuel consumption (gal/kg/km) * Cargo weight (kg) * Functional unit (vol) / Analysis Period (yr) / Volume treated (Vol/yr)

Fuel consumption estimates are found on the MD EFs worksheets. Other parameters are discussed in the Material Delivery Calcs section.

Direct Emissions: Direct emissions calculations are as follows:
Direct emissions (Mg) = (N_2O Emissions * N_2O GWP + Methane Emissions * Methane GWP) * Functional Unit (Vol) / Volume treated (Vol/yr)

Estimates of annual direct emissions for N_2O and methane can be edited by the user on the Assump- LTRT or STRT worksheet. Default estimates are calculated on the Calcs-GHG worksheet. N_2O global warming potential (GWP) is assumed to be 340 & methane GWP is assumed to be 23 (100 year time-frame). GWP values are found on the Conv worksheet.

Sludge Disposal: Sludge disposal calculations are specific to the disposal choice. They are discussed specifically on the Calcs-STRT page.

RECOMMENDED ORDER OF DATA ENTRY:

The first two columns in the table describe the worksheet name and code. The third column indicates whether entry on this sheet is required or optional. The last column indicates whether the user must click the "Enter Data" button at the bottom of the sheet before moving on to the next worksheet. Worksheet code is hyperlinked to its location in WWEST.

Worksheet Name	Wksht Code	Required/ Optional	Button Required?
Entry- General Information	Entry-GEN	Required	Yes
Assumptions- General Information	Assump-GEN	Optional	Yes
Assumptions- Equipment	Assump-EQUIP	Optional	Yes
Entry- Energy Production	Entry-EP	Required	No
Entry- Collection	Entry-COL	Required	Yes
Assumptions- Collection	Assump-COL	Optional	Yes
Entry- Treatment	Entry-TRT	Required	Yes
Assumptions- Liquid Treatment	Assump-LTRT	Optional	Yes
Assumptions- Process Liquid Trtmt	Assump-LTRT2	NA	No
Assumptions- Sludge Treatment	Assump-STRT	Optional	Yes
Assumptions- Process Sludge Trtmt	Assump-STRT2	NA	No
Entry- Discharge	Entry-DIS	Required	Yes
Assumptions- Discharge	Assump-DIS	Optional	Yes

Note: NA = Not currently activated.

DEVELOPER CONTACT INFORMATION:

Questions may be addressed to:

Jennifer Stokes, PhD
Research Associate
Consortium on Green Design and Manufacturing
University of California- Berkeley

Principal Investigator: Arpad Horvath
Associate Professor
Department of Civil and Environmental Engineering
University of California- Berkeley

HELP- ENTRY and ASSUMPTIONS worksheets

Jump to HELP Topic:

Entry- GENERAL
Assumptions- GENERAL
Assumptions- EQUIPMENT
Entry- ENTRY PRODUCTION
Entry- COLLECTION / DISCHARGE
Assumptions- COLLECTION / DISCHARGE
Entry- TREATMENT
Assumptions- LIQUID TREATMENT
Assumptions- SLUDGE TREATMENT

Return to:

Entry- General
Results- Graphs

Jump to Addditonal HELP worksheets:

Help- GENERAL
Help- RESULTS
Help- DEFAULT/CONVERSION and CALCULATIONS
Help- REFERENCES

ENTRY-GENERAL worksheet

RESET General Info Defaults button can be used to clear any data which has been entered and replace with tool defaults, where applicable.

Model Information

Unit Selection:	Select the units for data entry from the drop-down menu (U.S. or metric). Selecting units will run a macro to allow data entry in the selected units. Results are reported in metric units (g or MJ) regardless of selection.
Analysis Period:	Enter the analysis period in years. The analysis period should correspond to the design life or expected service life of typical materials so emissions are allocated correctly. Default value: 25
Functional units:	Enter the desired functional unit in units of MGD raw sewage (U.S.) or ML/d (metric). The functional unit should be large enough to allow comparison of results.

Project Information

Project Name:	Enter the name of the wastewater system being analyzed.
Project Location:	Select the state where the system is located from the drop-down menu. The state is used to determine the appropriate electricity emissions factors to use.
Service area demographics	Enter the approximate population and service area (in square miles or kilometers) served by the wastewater utility

Facility Information

WWTPs (No.):	Enter the number of WWTPs for which data will be entered. The selection will grey out unnecessary cells on this and following sheets.
Facility Name:	Enter the facility name, if desired.
Plant ID:	Enter a short code for each facility. This will be used on later pages to identify where data related to particular facilities will be entered.
Average inf. raw sewage:	Enter the average volume of raw sewage which enters the plant in units of MGD (U.S.) or ML/d (metric).
Maximum capacity:	Enter the maximum design capacity of the treatment plant in units of MGD (U.S.) or ML/d (metric).
Include in System?	Select either "yes" or "no" from the drop-down menu. If "yes" is selected, the data for the plant will be included in overall system results. If "no" is selected, the data for the plant will be analyzed as a separate entity and will not be incorporated into the overall system results.
Total system volume	Sums the values of both average influent sewage and maximum capacity for plants when "yes" is selected to indicate the plant should be included in the system.
Total volume	Sums the values of both average influent sewage and maximum capacity for all plants included in the Facility Information Table.

Enter GENERAL Information data button must be pressed when data on this worksheet has been completed. A macro will enter the appropriate data into later ENTRY worksheets and into the calculations. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly. Go to ENTRY

ASSUMPTIONS-GENERAL worksheet

RESET General Assumption Defaults button can be used to clear any data which has been entered and replace with tool defaults, where applicable.

Model Assumptions

GWE Time Horizon:	Select the desired time horizon for GWE calculations from the dropdown menu (50, 75, 100, or 500 years). The default value is 100 years.
Current year	The value of the current year is calculated automatically; it is used for discounting.
Primary cost year:	Enter the primary year for material purchase cost reporting. The value is used to discount costs for equipment, etc. for costs entered by the user prior to analysis.

Material Delivery Assumptions and Custom Materials

Material Choices:	The list provides all of the default materials available in WWEST. In addition, the user can add Custom Materials in the last fifteen lines.
Material Service Life:	The user may edit or enter the expected service life for each material. Service lives for custom materials must be entered.
Delivery Mode:	The user may select the appropriate delivery mode (local or long-distance truck, train, ship) from the drop-down menu.
Delivery Distance:	The user may edit or enter the delivery distance for each material. Delivery distance should be added for the Custom Materials.
Custom Materials Sector:	For custom materials, the user should select the appropriate economic sector from the drop-down menu. If the user isis not sure which sector to select, consult the sector definitions at eiolca.net. If an appropriate sector is not included in WEST, please contact the developers to have it added to the tool.

Enter GENERAL Assumptions data button must be pressed when data on this worksheet has been completed. A macro will enter the appropriate data into later ENTRY worksheets and into the calculations. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly. Go to ENTRY

ASSUMPTIONS-EQUIPMENT worksheet

RESET Equipment Defaults button can be used to clear any data which has been entered and replace with tool defaults, where applicable.

Equipment Entry Table

Equipment:	The column describes general categories of equipment. Additional equipment can be added by editing the information in the final 12 rows.
Typical Model:	The column describes a typical model within each category. Default data applies to this or a similar model.
Engine Capacity:	The engine capacity for the desired equipment should be entered in either horsepower (hp) or kilowatts (kW), depending on units selection. Default data can be edited by the user.
Power:	The power of electric-powered equipment can be edited or entered in watts.
Units:	The user can edit or enter the units for the appropriate emission factors. Hours should be used for off-road equipment (e.g., backhoes, graders). For on-road equipment, distance should be used in either miles or kilometers (km), depending on unit selection.
Fuel consump:	For non-electric-powered equipment, the fuel consumption can be edited or entered in units of volume per hour for non-road equipment or in units of distance per volume for road vehicles.
Fuel type:	The column indicates the energy source for the equipment (diesel, gasoline, or electric).
Emissions factors:	The energy consumption and emission factors for each equipment type can be entered or edited in units of grams per hour for non-road equipment or per distance for road vehicles, as indicated in Column E.
Equipment Efficiencies:	The user can edit or enter the efficiency for construction equipment and construction-related road equipment.

ENTRY-ENERGY PRODUCTION worksheet

RESET Energy Production Defaults button can be used to clear any data which has been entered and replace with tool defaults, where applicable.

Energy Mix Selection

Emission Factors	The user should select the desired emission factors (EFs) to be used in energy calculations. The user can select direct emissions (i.e., smokestack) or life-cycle emissions (i.e., upstream effects are included). The Natural Gas EFs are updated automatically based on selection.
Electricity Scenario	The user should select the desired electricity mix to be used in energy calculations (national average mix, state average mix, or custom generation mix). The appropriate default electricity Efs are updated automatically based on selection.

Electricity Default Data and Emission Factors Table

The data in this table is updated automatically based on the energy mix selections made above. Greyed out cells are not relevant based on the above selections.

Natural Gas and Fuel Emission Factors Table

The data in these tables is updated automatically based on the emission factors selections made above. Fuel emission factors are only available for life-cycle emissions.

ENTRY-COLLECTION/DISCHARGE worksheet **COLLECTION** **DISCHARGE**

The ENTRY pages for the Collection and Discharge systems are virtually identical. The HELP information for these worksheets is presented jointly.

Clear Entry-Collection (Discharge) Data button can be used to clear any data which has been entered. COLLECTION DISCHARGE

Pipeline Material Production Estimates table contains data on pipes in the collection/discharge system. It can be entered on a system-wide basis or can be specifically identified with any user-defined WWTP. Each length of pipe or other material should be entered EITHER as part of the overall system OR for a WWTP. Avoid double-counting of materials. To simplify data entry, pipe information is broken down into categories by diameters: > 36 in. (> 91 cm), 12 - 36 in. (30 - 91 cm), and <12 in. (< 30 cm). For the system and/or WWTP, the following data should be entered: COLLECTION DISCHARGE

Pipe Length: Enter the length of pipe for each diameter category in units of ft or m, depending on unit selection.

Valves: Enter the number of valves in each diameter category. All valves (e.g., check, globe, butterfly) should be included in the total.

Pipe Material Breakdown table allows the user to indicate the proportion of piping which is composed of various materials. The material breakdown is assumed to be the same for the overall system and each WWTP. The percentage of pipe from each material for each diameter category should be entered in the table. The user should ensure the sum of all materials is 1. COLLECTION DISCHARGE

Manholes table (COLLECTION only) allows the user to enter the number of each size and type of manholes used in the collection system. The number for the overall system and others associated with specific WWTPs may be entered. COLLECTION

Type: Select the manhole material from the drop-down menu, either cast-in-place or precast concrete.

Depth: Select the manhole depth from the drop-down menu in units of feet or meters, depending on unit selection.

Inner Diameter: Select the manhole inner diameter from the drop-down menu in units of feet or meters, depending on unit selection.

Curb inlets table (COLLECTION only) allows the user to enter the number of each size and type of curb inlets used in the collection system. The number for the overall system and/or others associated with specific WWTPs may be entered. COLLECTION

Lift Stations and Pumps table allows the user to define the number of lift stations and the number of associated pumps. Construction information about lift stations can be defined on the Assumptions-COL (or DIS) worksheet. The following information should be entered. COLLECTION DISCHARGE

Lift Station Facilities: The user should enter the number of lift stations associated with the overall system and/or associated with a particular WWTP.

Total Pumps: The user should enter the number of pumps within each size category associated with the overall system and/or associated with a WWTP. Pumps within plants should be entered on the Treatment pages.

Annual Energy Sources table allows the user to define the quantities of energy consumed by the collection or discharge system each year. Energy consumption can be entered either for the entire system or a particular WWTP. COLLECTION DISCHARGE

Electricity: Annual gross electricity consumption should be entered in units of MWh.

Natural gas: Annual gross natural gas consumption should be entered in units of MMBTU.

Gasoline & Diesel: Annual fuel consumption for generator and facility operation should be entered in units of liters or gallons, depending on unit selection. Fuel consumption for material delivery is calculated automatically. If the user enters information on equipment use, associated fuel consumption will be calculated automatically.

Additional Material Entry table allows the user to enter information on materials consumed in the collection or discharge system which has not been captured by earlier tables. COLLECTION DISCHARGE

Life-cycle Phase: Select the appropriate life-cycle phase (construction, operation, or maintenance) from the drop-down menu. A life-cycle phase should be selected for every material entered in the table.

Material: Select the appropriate material from the drop-down menu. If a material needs to be added to the list, custom materials can be added at the bottom of the table on the "Assumptions-GENERAL" worksheet.

Pay Schedule — Select the appropriate pay schedule (one time, once per service life, or annually) from the drop down ment for each material.
Cost — Enter the cost for the material for the appropriate pay schedule, i.e., if the pay schedule is annual, enter the annual cost; if it is once per service life, enter the cost per purchase cycle.
Weight — Enter the weight for the material for purchase cycle (annual, one time, etc.). If weight is not entered, material delivery calculations will be incomplete.

Operational Equipment Use table allows the user to enter information on equipment used as part of the collection/discharge system life-cycle. Some equipment used for constuction is calculated automatically (see "Calculations- Collection" (or Discharge) worksheet). User should be careful to avoid double-counting.
COLLECTION DISCHARGE

Enter COLLECTION (DISCHARGE) data button must be pressed when data on this worksheet has been completed. A macro will enter the appropriate data into later ENTRY worksheets and into the calculations. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly.
COLLECTION DISCHARGE

ASSUMPTIONS-COLLECTION/DISCHARGE worksheet

The Assumptions pages for the Collection and Discharge systems are virtually identical. The HELP information for these worksheets is presented jointly.

RESET Assumption-Collection (Discharge) Defaults button can be used to clear any data which has been entered and replace with tool defaults, where applicable. COLLECTION DISCHARGE

Pipe Assumptions table allows the user to enter the average pipe depth for each pipe diameter. Also, the user can define an assumption for how often fittings are needed in the piping system. COL DIS

Pump and Lift Stations Assumptions table allows the user to enter the average pipe depth for each pipe diameter. Also, the user can define the frequency per pipe length of fittings in the piping system. Data for other facilities or buildings can also be entered in the lower section of the table. COL DIS

Other buildings — In the lower part of the table, select from the drop-down menu the appropriate part of the collection system associated with the additional buildings defined in the table. This information is entered automatically from the ENTRY-Assumptions page for the upper part of the table.
Average area — Enter the average area per pump station or other facility in units of sf or m2, depending on the units selection.
Wall height — Enter the wall height for an average facility in units of ft or m, depending on the units selection. If the facility is just a foundation, the wall height can be zero.
Above/below ground: — Select from the drop-down menu whether the facility is above or below ground. If unknown or a combination, the user can select "average".
Number of stations — In the lower part of the table, enter the number of facilities covered by each of the defined facilities. This information is entered for the life stations on the ENTRY- Collection worksheet.

Enter COLLECTION (DISCHARGE) Assumption data button must be pressed when data on this worksheet has been completed. A macro will enter the appropriate data into later ENTRY worksheets and into the calculations. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly. COLLECTION DISCHARGE

ENTRY-TREATMENT worksheet

RESET Default Treatment Data button can be used to clear any data which has been entered and replace with tool defaults, where applicable. Go to ENTRY

Plant Summary Table allows the user to enter custom data about each plant's general operational parameters. Go to ENTRY

Average inf. volume: — These values are transferred automatically from daya entered on the ENTRY-General worksheet. Necessary edits should be made there.
Concentrations — The user may choose to enter data about influent BOD, Total N, Total P concentrations and effluent N in water and BOD content in sludge. These are used to estimate greenhouse gas emissions and/or fertilizer offsets for ground application. Data should be entered in mg/L in liquid and mg/kg in sludge.
Treatment Processes: — The table should be used by the user to select the treatment processes included at each WWTP. An "X" should be entered for each process utilized. The processes selected affect default calculations for electricity consumption, greenhouse gas emissions, and sludge production. More detailed data about each process can be entered on the ASSUMP-LTRT or ASSUMP-STRT worksheet. If a process wasn't selected for a particular WWTP, the associated row or column on the ASSUMPTION sheets may be grayed out.

Piping Material Production Estimates table contains data on pipe and appurtences in each WWTP.

To simplify data entry, pipe information is broken down into categories by diameter. For the liquid plant, pipe above and equal to or below 12-inch (30 cm) diameter are entered in separate categories. For sludge processing, the cutoff between categories is 18 inches (46 cm). Go to ENTRY

Pipe Length: Enter the length of pipe for each diameter category in units of ft or m, depending on unit selection.

Valves: Enter the number of valves in each diameter category. All valves (e.g., check, globe, butterfly) should be included in the total.

Flowmeters: Enter the number of flowmeters in each diameter category.

Pump Material Production Estimates table allows the user to define the number of pumps at each facility used for liquid and sludge processing. In each case, the number should be ntered within the designated power ranges. Go to ENTRY

OPERATION

Annual Energy Sources table allows the user to quantify the energy consumed at each WWTP per year. Energy use should be separated into liquid and solid treatment processes, if possible. Go to ENTRY

Electricity Annual gross electricity consumption should be entered in units of MWh. Default values are calculated based on the processes selected above. However, these estimates are based primarily on aeration electricity and may not be comprehensive. The default electricity use calculations and associated assumptions are calculated on the CALCS-Elect-Sludge worksheet. No edits should be made to the Calculations worksheet.

Natural gas Annual gross natural gas consumption should be entered in units of MMBTU.

Gasoline & Diesel Annual fuel consumption for generator and facility operation should be entered in units of liters or gallons, depending on unit selection. Fuel consumption for material delivery is calculated automatically. If the user enters information on equipment use, associated fuel consumption will be calculated automatically.

Annual Energy Recovery table allows the user to define the quantities of energy recovered at each WWTP annually. Energy recovery should be separated into liquid and solid treatment processes, if possible.

Electricity Annual gross electricity recovered should be entered in units of MWh. Go to ENTRY

Heat This alternative is not yet active.

Annual Chemical Consumed table allows the user to define the quantities of chemicals consumed at each WWTP annually. Chemical consumption should be separated into liquid and solid treatment processes, if possible. Go to ENTRY

General information is chemical- specific and used for calculations at all plants where the chemical is used. User should enter either cost or density, as indicated by purple cells.

Cost: If the cell has not been grayed out, enter the cost per unit volume (in $/l or $/gal). Cost is only needed if EIO-LCA emission factors are used for that chemical. If not, cell will be grayed out.

Chemical density: If the cell has not been grayed out, enter the density (in kg/l or lb/gal). Density is only needed if process-based emission factors are used for chemical. If not, cell will be grayed out.

Plant information is only applicable to a particular WWTP.

Chemical vol: Enter the volume of each chemical used at each facility (in l or gal).

Delivery distance: Enter the distance between the manufacturing location, if possible, or distributor location and the WWTP (in miles or km).

Storage tanks: Enter the number of storage tanks needed to store the chemicals on-site. The tanks are assumed to be be steel.

Tank size: Enter the volume of chemical in each tank (in l or gal). If multiple sizes are used, enter the average value.

Annual Sludge Production table allows the user to define the quantities of sludge produced at each WWTP annually. Default values are estimated on the CALCS-Elect-Sludge worksheet but should not be edited there. Go to ENTRY

Primary: Enter the annual volume of sludge produced from primary treatment (in m3 or cy).

Secondary/ Tertiary: Enter the annual volume of sludge produced from secondary and tertiary treatment (in m3 or cy).

Sludge to be treated (wet) The wet volume of sludge to be treated through the sludge treatment is the sum of primary and secondary/tertiary sludge

Sludge to be treated (dry) Edit the dry volume of sludge to be treated throught sludge treatment. The default dry volume of sludge is estimated assuming a solids content of 1.5% for the combined sludge volume.

Sludge to be disposed Edit the wet volume of sludge after the sludge treatment process which must be transported to and disposed at the final disposal site.

Annual Greenhouse Gas Emissions Capture table allows the user to enter the percentage of GHG captured or flared at each WWTP annually for specific liquid treatment, sludge treatment, and disposal options. Emissions volumes can be edited on the ASSUMP-LTRT and ASSUMP-STRT worksheets, respectively. Go to ENTRY

Additional Material Entry table allows the user to enter information on materials consumed in the treatment system which has not been captured by earlier tables. Go to ENTRY

Life-cycle Phase	Select the appropriate life-cycle phase (construction, operation, or maintenance) from the drop-down menu. A life-cycle phase should be selected for every material entered in the table.
Material	Select the appropriate material from the drop-down menu. If a material needs to be added to the list, custom materials can be added at the bottom of the table on the "Assumptions-GENERAL" worksheet.
Pay Schedule	Select the appropriate pay schedule (one time, once per service life, or annually) from the drop down ment for each material.
Cost	Enter the cost for the material for the appropriate pay schedule, i.e., if the pay schedule is annual, enter the annual cost; if it is once per service life, enter the cost per purchase cycle.
Weight	Enter the weight for the material for purchase cycle (annual, one time, etc.). If weight is not entered, material delivery calculations will be incomplete.

Operational Equipment Use table allows the user to enter information on equipment used as part of the treatment system life-cycle. Some equipment used for constuction is calculated automatically (see "Calculations- Treatment" worksheet). User should be careful to avoid double-counting. Go to ENTRY

Enter TREATMENT data button must be pressed when data on this worksheet has been completed. A macro will enter the appropriate data into later ENTRY worksheets and into the calculations. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly. Go to ENTRY

ASSUMPTIONS-LIQUID TREATMENT worksheet

RESET General Liquid Treatment Defaults button can be used to clear any data which has been entered about wall thickness and population served by plants with tool defaults, where applicable. To reset process-specific data, reclick the Enter button on the ENTRY-TRT worksheet. Go to ENTRY

General Assumptions Go to ENTRY

Process Wall Thickness Table allows the user to enter custom data about wall thicknesses for plant process components, depending on material (concrete or steel) and tank depth.

Population Table allows the user to enter the number of customers (total population) served by each plant. These numbers are used to set default parameters for each plant.

Enter General LIQUID TREATMENT assumptions button must be pressed when data in this upper General Assumptions section has been completed. These values will set defaults used in the process-specific data entry below. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly. Go to ENTRY

Greenhouse Gas Emission Calculations Table allows the user to edit default estimates of greenhouse gas emissions. Default values are based on IPCC 2006 protocols. Units are Mg/yr. Go to ENTRY

Detailed Treatment Process Assumptions

Plant ID, as defined by the user on the Entry-GEN worksheet, must be selected for all lines of data entry.

Septic Tank Table allows the user to enter custom data about septic tanks. Go to ENTRY

Tanks (#)	Enter the number of septic tanks included in the system.
Tank Material	Select the tank material (concrete, fiberglass, plastic) from the drop-down menu.
Compartments	Select the number of compartments in the septic tank (1 or 2).
Dimensions	User should enter the appropriate dimensions for the average storage basin (in feet or meters).
Cleaning Frequency	The user should enter the approximate frequency of routine tank cleanings and sludge disposal in terms of years.

Fine/Micro Screening Table allows the user to enter custom data about screening equipment

Technology Type	User should select the technology type from the drop-down menu (inclined fixed screen, rotary drum, horizontal reciprocating, or tangential). Go to ENTRY
Equipment	Enter the number of screens defined in Column D at the facility.
Equip Cost	Enter the cost for each screening unit at the appropriate facility.
Basin Size	If the screen is located in a separate basin or on a pad, enter the dimensions for length, width, and depth (in ft or m). Basin is assumed to be reinforced concrete.

Grinding Table allows the user to enter custom data about grinding equipment

Technology Type	User should select the technology type from the drop-down menu (grinder, macerator, or comminutor). Go to ENTRY
Equipment	Enter the number of grinding units defined in Column D at the facility.
Equip Cost	Enter the cost for each grinding unit at the appropriate facility.

Grit Removal Table allows the user to enter custom data about grit removal equipment Go to ENTRY

Equipment	Enter the number of grit removal units.
Technology Type	User should select the technology type from the drop-down menu (horizontal flow, aerated, or vortex).
Tank Material:	User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Dimensions	User should enter the appropriate dimensions for the technology type selected. Depth is needed for all technologies. If vortex removal is selected, enter the upper and lower diameters in columns H and I, respectively. For other technologies, enter the width and length.
Equip Cost	Enter the cost for each grit removal unit at the appropriate facility.

Flow equalization/storage Table allows the user to enter custom data about storage facilities. The basins are assumed to be rectangular. Go to ENTRY

Total Storage Capacity	Enter the total storage capacity for all basins which are used for flow equalization or overflow storage (in MG or ML).
Basins	Enter the number of storage basins located at each facility.
Tank Material:	User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Mixed or baffled?	User should select the means of mixing, if appropriate, from the drop-down menu (mechanical mixing or static baffles).
Aerated?	User should indicate whether the basins are aerated by selecting yes or no from the drop-down menu.
Dimensions	User should enter the appropriate dimensions for the average storage basin (in feet or meters).
Mixer Cost	Enter the cost of mixers installed in the average basin.
Aerator Cost	Enter the cost of aerators installed in the average basin.

Rapid Mix Basin Table allows the user to enter custom data about rapid mix processes. The basins are assumed to be square. Go to ENTRY

Basins	Enter the number of rapid mix basins located at each facility.
Tank Material:	User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Dimensions	User should enter the appropriate dimensions for the average basin (in feet or meters).
Mixer Cost	Enter the cost of mixers installed in the average basin.

Coagulation/Flocculation Table allows the user to enter custom data about coagulation and flocculation processes. Go to ENTRY

Basins	Enter the number of coagulation/flocculation tanks located at each facility.
Tank Material:	User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Mixed or baffled?	User should select the means of mixing, if appropriate, from the drop-down menu (mechanical mixing or static baffles).
Dimensions	User should enter the appropriate dimensions for the average basin (in feet or meters).
Mixer Cost	Enter the cost of mixers installed in the average basin.

Sedimentation/Clarification Table allows the user to enter custom data about sedimentation and clarification processes. Go to ENTRY

Basins	Enter the number of sedimentation and/or clarification tanks located at each facility.
Treatment Stage	User should select the treatment stage assocated with the particular tank (primary or secondary) from the drop-down menu.
Tank Material:	User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Tank Shape	User should select whether the tank is circular or rectangular from the drop-down menu.
Dimensions	User should enter the appropriate dimensions for the average basin (in feet or meters). If the tank is rectangular, enter the depth, width, and length. If circular, enter depth, bottom slope, and diameter.
Clean. Equip	Enter the cost of equipment used to clean sludge from the tank installed in the average basin.
Other Equip	Enter the cost of all other equipment used to clean sludge from all basins of that type and size.

Conventional (Depth) Filtration Table allows the user to enter custom data about non-membrane filtration processes. Go to ENTRY

Trtmt Trains:	Enter the number of filter tanks located at each facility.
Medium depth:	User should enter the depth (in feet or meters) for the depth of each medium type (sand, anthracite, garnet sand, synthetic, and gravel underdrain).
Tank Material:	User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).

Tank Shape	User should select whether the tank is circular or rectangular from the drop-down menu.
Dimensions	User should enter the appropriate dimensions for the average basin (in feet or meters).
Med. Replcmt Rate	Enter the number of years that each the medium is expected to last before it needs to be replaced.
BW Equip	Enter the cost of equipment used to backwash the tanks per filter tank.
Other Equip	Enter the cost of all other equipment used to clean sludge from all basins of that type and size.

Membrane Filtration Table allows the user to enter custom data about membrane filtration processes.

Membrane Type:	User should select the type of membrane from the drop-down menu (microfiltration, ultra-filtration, nanofiltration, and reverse osmosis). Go to ENTRY
Membrane Material:	User should select the membrane's primary material from the drop-down menu (e.g., PPE, cellulose acetate, polyamides, thin film composite).
Trtmt Trains:	Enter the number of membrane trains located at each facility.
Membrane #	Enter the number of membranes per treatment train.
Mmbrn. Cost	Enter the cost of each membrane.
Mmbrn. Wt	Enter the weight of each membrane (in pounds or kilograms).
Mmbrn life	Enter the expected life of each membrane (i.e., time to replacement) in years.
Equip Cost	Enter the cost of all equipment used to clean and operate each membrane train.
Elect use	Enter the electricity use associated with membrane use in kWh/yr.

Activated Sludge Table allows the user to enter custom data about activated sludge processes.

AS Type	For each plant, one means of activated sludge may be entered automatically based on selections made by the user on the Entry-GEN worksheet. Go to ENTRY
Trmt Trains	Enter the number of activated sludge basins or treatment trains located at each facility.
Dimensions	User should enter the appropriate dimensions for the average basin (in feet or meters). The basins are assumed to be square; only depth and one side length measurement are needed. The basin is assumed to be constructed of concrete.
AS Equip	Enter the cost of equipment used in the activated sludge processes installed in the average basin.
N or P Removal	User should indicate whether nitrogen and/or phosphorus removal processes by selecting yes or no for each from the drop-down menu.
Nut. Tanks	Enter the number of nutrient removal tanks located at each facility.
Dimensions	User should enter the appropriate dimensions for the average basin (in feet or meters). The basins are assumed to be square; only depth and one side length measurement are needed.
Nut Rem Equip	Enter the cost of equipment used in the nutrient removal processes installed in the average basin.
Other Equip	Enter the cost of all other equipment used to clean sludge from all basins of that type and size.

Pond and Lagoons Table allows the user to enter custom data about pond or lagoon based processes. Two types of ponds can be entered for each plant but the data entry is identical for each. Go to ENTRY

Pond Type	User should select the type of pond or lagoon from the drop-down menu (facultative, anaerobic, facultative aerated, sedimentation, completely mixed aerated, maturation). The first pond type may be entered automatically based on user entry on the Entry-TRT worksheet.
Ponds #	Enter the number of ponds or lagoons of each type located at each facility.
Dimensions	User should enter the appropriate dimensions for the average pond of each type (in feet or meters).
Equip Costs	Enter the cost of the liner, biogas cover, and other equipment needed per pond or lagoon.

Carbon Adsorption Table allows the user to enter custom data about carbon adsorption processes.

Carbon Type:	User should select the type of carbon material from the drop-down menu (granular or powdered). Go to ENTRY
Trtmt Trains:	Enter the number of carbon trains located at each facility (a train may be multiple vessels).
Vessels #	Enter the number of carbon vessels per treatment train.
Tank Volume	Enter the volume of each carbon vessel (in liters or gallons).
Carbon Wt	Enter the weight of each carbon in each vessel (in pounds or kilograms).
Carbon life	Enter the expected life of the carbon (i.e., time to replacement) in years.
Equip Cost	Enter the cost of all equipment used to clean and operate each carbon vessel train.

Membrane Bioreactors (MBR) Table allows the user to enter custom data about membrane bioreactors.

MBR Type	User should select the type of MBR from the drop-down menu (seperation, aeration, or extractive). Go to ENTRY
Aerobic?	Select the treatment mode (aerobic or anaerobic) from the drop-down menu.
Configuration?	Select the treatment mode (sidestream or submerged) from the drop-down menu.
Membrane Matl	Select the membrane material from the drop-down menu.

Carbon Wt Enter the weight of each carbon in each vessel (in pounds or kilograms).
Carbon life Enter the expected life of the carbon (i.e., time to replacement) in years.
Equip Cost Enter the cost of all equipment used to clean and operate each carbon vessel train.
Train # Enter the number of treatment trains.
MBRs per train Enter the number of MBR cartridges per treatment train.
MBR Cost Enter the cost per MBR cartridge in dollars.
MBR Life Enter the average life for each MBR cartridge in years.

Chlorine-based Disinfection Table allows the user to enter custom data about chlorine disinfection, including chlorine, chloramines, sodium hypochlorite, and chlorine dioxide. The user can also enter information on the declorination process, if applicable, either combined with chlorination data or separately. The data required for both is identical and is not described separately. Go to ENTRY

Chemical User should select the chemical disinfectant employed from the drop-down menu. Choices are listed above.
Dechlor? Select yes or no from the drop-down menu to indicate whether declorination is included in the treatment process.
Dimensions User should enter the appropriate dimensions for the chlorine contact basin (in feet or meters). The declorination dimensions can be entered separately or in this column, as desired.
Equip Cost Enter the cost of all equipment used to clean and operate each carbon vessel train.

Ozone Disinfection Table allows the user to enter custom data about ozone disinfection.

Ozone used? Select yes or no from the drop-down menu to indicate whether ozone is used.
Dose Enter the ozone dose in mg/l. Go to ENTRY
Basins # Enter the number of ozone contact basins located at each facility.
Dimensions User should enter the appropriate dimensions for each contact basin of each type (in feet or meters).
Equip Cost Enter the cost of all equipment used in each ozone basin.
Elect use Enter the electricity use associated with oxone use in kWh/yr.

Ultraviolet Disinfection Table allows the user to enter custom data about UV disinfection.

UV used? Select yes or no from the drop-down menu to indicate whether ozone is used.
Dose Enter the UV dose in mJ/cm3. Go to ENTRY
Basins # Enter the number of UV contact channels located at each facility.
Lamps/channel Enter the number of UV lamps needed per channel.
Dimensions User should enter the appropriate dimensions for each contact basin of each type (in feet or meters).
Elect use Enter the electricity use associated with oxone use in kWh/yr.
Elect use Enter the electricity use associated with oxone use in kWh/yr.

Enter LIQUID TREATMENT assumptions button must be pressed when this worksheet has been completed. A macro will enter the appropriate data into later ENTRY worksheets and calculations. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly. Go to ENTRY

ASSUMPTIONS-SLUDGE TREATMENT worksheet

RESET Sludge Treatment Defaults button can be used to clear any data which has been entered by the user and enter calculated defaults. Go to ENTRY

General Assumptions

Greenhouse Gas Emission Calculations Table allows the user to edit default estimates of greenhouse gas emissions. Default values are based on IPCC 2006 protocols. Units are Mg/yr. Go to ENTRY

Detailed Sludge Treatment Process Assumptions

Plant ID, as defined by the user on the Entry-GEN worksheet, must be selected for all lines of data entry.

Grinding Table allows the user to enter custom data about grinding equipment Go to ENTRY

Technology Type User should select the technology type from the drop-down menu (grinder, macerator, or comminutor).
Equipment Enter the number of grinding units defined in Column D at the facility.
Equip Cost Enter the cost for each grinding unit at the appropriate facility.

Flow equalization/storage Table allows the user to enter custom data about storage facilities. The basins are assumed to be rectangular. Go to ENTRY

Total Storage Capacity Enter the total storage capacity for all basins which are used for flow equalization or overflow storage (in MG or ML).
Basins Enter the number of storage basins located at each facility.
Average Capacity Enter the capacity of the storage basin volume utilized on average through the year as a percentage of total volume.

Tank Material: User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Mixed or baffled? User should select the means of mixing, if appropriate, from the drop-down menu (mechanical mixing or static baffles).
Dimensions User should enter the appropriate dimensions for the average storage basin (in feet or meters).
Equip Cost Enter the cost of mixers installed in the average basin.

Mechanical Thickening Table allows the user to enter custom data about mechanical sludge thickening, including centrifuge, filter/ belt press, vacuum filter, rotary drum filter, & thermal drying. Go to ENTRY

Equip # Enter the number of each type of equipment at the respective treatment plant
Equip. Type User should select the type of technology used from the drip-down menu (see list above).
Equip Cost Enter the cost of mixers installed in the average basin.
Hours of Use User should enter the average hours of use each day for the respective plant.

Gravity Thickening Table allows the user to enter custom data about gravity thickening and flotation processes. Go to ENTRY

Thickeners: Enter the number of gravity thickening and flotation tanks located at each facility.
Tech Type User should select the treatment type (gravity or flotation) from the drop-down menu.
Tank Material: User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Dimensions User should enter the appropriate dimensions for the average basin (in feet or meters). The tank is assumed to be circular.
diameter.
Clean. Equip Enter the cost of equipment used to clean sludge from the tank installed in the average basin.
Other Equip Enter the cost of all other equipment used to clean sludge from all basins of that type and size.

Drying Bed and Lagoon Table allows the user to enter custom data about lagoon based drying processes.

Bed Type User should select the type of drying bed or lagoon from the drop-down menu (conventional sand, paved, reed bed, or lagoon). Go to ENTRY
Bed # Enter the number of beds or lagoons of each type located at each facility.
Bed/Fdtn Material User should select the material which lines the pond and walls from the drop-down menu (concrete, earthen, and asphalt).
Clean Mthd User should select the cleaning method (mechanical or manual) from the drop-down menu.
Mixing User should indicate whether the lagoon is mixed using the drop-down menu (yes or no).
Dimensions User should enter the appropriate dimensions for the average pond of each type (in feet or meters).
Equip Costs Enter the cost of equipment needed per pond or lagoon.
Other Equip Enter the cost of all other equipment needed for the drying ponds.

Digestion Table allows the user to enter custom data about digestion processes used for stabilization. Reactors are assumed to be cylindrical and concrete. Go to ENTRY

Technology Type User should select the technology type from the drop-down menu (conventional aerobic, pure oxygen, thermophilic, and anaerobic).
Trains # Enter the number of digestion tanks or treatment trains located at each facility.
Dimensions User should enter the appropriate dimensions for the average reactor (in feet or meters).
Equip Costs Enter the cost of aeration equipment needed per reactor.
Other Equip Cost Enter the cost of all other equipment needed for the digestors. This may include pure oxygen generation equipment.

Chemical-based Treatment Table allows the user to enter custom data about chemical use for treatment, including stabilization, conditioning, thickening, and pathogen removal. The chemicals used should be entered on the Entry-TRT worksheet. Go to ENTRY

Tank # Enter the number of chemical mixing/contact tanks or treatment trains located at each facility.
Tank Material: User should select the material from which the tank is constructed from the drop-down menu (concrete or steel).
Dimensions User should enter the appropriate dimensions for the average basin (in feet or meters).
Mix Equip Cost Enter the cost of mixing equipment installed in the average basin. Other equipment can be entered here as well.

<u>Detailed DISPOSAL Assumptions</u>

Land Application Table allows the user to enter custom data about solids disposal via land application. Transport is assumed to be by dump truck. Go to ENTRY

Solid dspsd Enter the percentage of the total solids volume which is disposed via land application.
Fertilizer? Indicate whether the land-applied solids are used to offset commercial fertilizer production.
Applic Mtd User should select the appropriate application method (wet or dry) from the drop-down menu.

Applic Rate — Enter the rate of solids applied in lb/sf or kg/m2.
Storage pd — Enter the average storage period for solids prior to land application.
Disposal distance — Enter the average distance solids are transported to reach the land application disposal site in miles or km.

Landfill Table allows the user to enter custom data about solids disposal via landfill. Transport is assumed to be dump truck. If gas is recovered, enter the recovery rate on Entry-TRT worksheet. Go to ENTRY

Solid dspsd — Enter the percentage of the total solids volume which is disposed via land application.
Gas Recvry — Indicate whether a gas recovery system is present at the landfill.
Gas Trtmt — Indicate type of landfill gas treatment, if applicable (flared, electricity generation, or unknown).
Disposal distance — Enter the average distance solids are transported to reach the land application disposal site in miles and km.

Incineration Table allows the user to enter custom data about disposal via incineration. Transport is assumed to be dump truck. If energy is recovered, enter recovery rate on Entry-TRT worksheet. Go to ENTRY

Solid dspsd — Enter the percentage of the total solids volume which is disposed via land application.
Inc Type — Select the incinerator type (multiple hearth or fluidized bed) from the drop-down menu.
Incinerators # — Enter the number of incinerators used for sludge disposal.
Dimensions — Enter the height and diameter of the incinerator (in feet or meters) for both the incinerators and cooling towers.
Equip Cost — Enter the cost of equipment associated with incinerators as a total.
Incin distance — Enter the average distance solids are transported to reach theincinerator site in miles or km.
Ash condition — Select from the drop down menu whether the ashes are disposal wet or dry.
Ash disposal — Select from the drop down menu whether the ashes are in a lagoon, a landfill, or re-used in an industrial application.
Disp distance — Enter the average distance ash is transported to reach the final disposal site in miles or km. miles and km.

DISPOSAL Emission Factors Table contains disposal emission factors for different disposal scenarios, as appropriate. Defaults values are available for certain options (landfill, incineration, composting). Default values can be found on the Disposal and/or the Calcs-GHG worksheets. The user can edit these values or add values for other disposal alternatives. Go to ENTRY

Enter SLUDGE TREATMENT assumptions button must be pressed when data on this worksheet has been completed. A macro will enter appropriate data into later ENTRY worksheets and calculations. If the button is not pressed prior to moving to the next sheet, calculations may not progress correctly. Go to ENTRY

HELP- DEFAULT, CONVERSION and CALCULATIONS worksheets

Jump to HELP Topic:
DEFAULTS worksheets
CONVERSIONS worksheets
Calculations- ENERGY PRODUCTION
Calculations- COLLECTION
Calculations- LIQUID TREATMENT
Calculations- SLUDGE TREATMENT
Calculations- DISCHARGE
Calculations- Greenhouse Gases

Return to:
Entry- General
Results- Graphs

Jump to Addditonal HELP worksheets:
Help- GENERAL
Help- ENTRY
Help- RESULTS
Help- REFERENCES

DEFAULTS worksheets

The cells in this section are used to reset default values on the Entry and Assumption worksheets. The user can edit these values on the appropriate worksheets. Values are shown in both units & are transferred to the Entry and Assumption worksheets depending on the units selected on the ENTRY-General worksheet.

CONVERSIONS worksheets

The cells in this section have been converted to a certain unit needed for the calculations. Data is added and converted when the "ENTER DATA" button at the bottom of the Entry-COL worksheets is clicked. Values may not be calculated correctly without clicking the button. Calculations are straightforward conversions to the units indicated for each table. Conversion factors are found on the CONV worksheet.

CALCULATIONS-ENERGY PRODUCTION worksheet

Selected Emission Factors Table transfers emission factors for the selected electricity mix and natural gas from the Entry-EP worksheet for use in the calculations which are completed on the Results-EP worksheet.

Energy Sources table calculates the contribution of different energy sources to the various life-cycle phases, wastewater phases, and facilities. Energy Production Eq.

Electricity — Electricity use associated with construction equipment is added to operational electricity use. The calculation is completed as follows:
Equip Electric (MWh/FU) = Hrs of Use *Power (watt) /1000000 /Annual Production
Operational Electric (MWh/FU) = Annual electric use (MWh) *Functional Unit / Annual Production

Recovery — Operational electricity recovered as part of the the treatment processes is subtracted from the electricity use. It is calculated in the same way as operational electricity use above.

Natural Gas — Natural gas is only accounted for in the operation phase.
Operational Natural Gas (MMBTU/FU) = Annual natural gas (MMBTU) *Functional Unit / Annual Production

CALCULATIONS-COLLECTION/DISCHARGE worksheet

The CALCULATION pages for the Collection and Discharge systems are virtually identical. The HELP information for these worksheets is presented jointly.

Summary Calculations are divided by facility (system or particular WWTP) and by life-cycle phase (construction, operation, and maintenance). **Material Production** calculations are divided further into material type (construction materials, equipment, chemicals, piping, and other). Results are shown for each of the evaluated chemicals (energy use, GWE,Nox, PM, SOx, VOC, and CO). **Material Delivery** calculations are compiled for different transportation modes (local truck, long distance truck, train, ship, and plane. **Equipment use** is summarized by miles driven or hours used for the different equipment alternatives considered in WWEST. **Fuel consumption** combines information from the material production data entry (fuel materials), materual delivery for all modes, and equipment use.

Equipment Use Assumptions include equipment efficiency (defined on the Assupmtions-GENERAL worksheet), pipe depth (from the Assumptions-COLLECTION or DISCHARGE worksheet), excavation depth (pipe depth + 2 feet), and excavation width (pipe dia. *1.5 for largest pipe; pipe dia. * 2 for smaller pipe). The hourly output for excavators sized appropriately for each excavation size are also included. Equipment data from the "EU Data" worksheet.

Pipeline Assumptions table lists costs & unit weights for piping, valves, & fittings of various material types. If the emission factor source is EIOLCA, pipe costs are provided; if process-based, weights are calculated. Cost information can be found on the "Cost Assump" worksheet.

Pipeline Calculations are provided for 3 diameter ranges for COLLECTION and 2 ranges for DISCHARGE and are divided by facility (system or WWTP) and material type.

Cost year — 1997 is used as the cost year because EIOLCA and the cost source are based in that year.

Piping	This cell calculates the total length for each type of pipe in feet.
	Length (ft) = Total Length (ft) * Material Breakdown (%), as defined on ENTRY page.
Valves	The number of valves is transferred from the ENTRY page.

Material Production Calculations for piping, valves, and fittings

Pipe materials	The cells calculates material production effects for the three diameter categories using the Material Production equation for process-based (plastics) & EIO-LCA (others) on the Help-GEN worksheet. For EIO-LCA, the unit cost is listed in the Pipeline Assumptions table. (Source: Means 1998). For process-based, the weight is calculated in the Pipeline Assumptions table based on data found on the Cost Assump worksheet. Material Production Eq.
Construction Phase Results	The cells calculate emissions associated with the initial material purchase for construction for all impact categories using the Material Production equation. The total piping cost or weight is the sum of results for piping, valves, & fittings. The emission factor (EF) is from EIOLCA or process-based (see Pipeline Assumptions table) & can be found on the airefs and waterefs worksheet. Emission factors are specific to each impact category.
Maintenance Results	The cells calculate effects associated with subsequent purchases for system maintenance for all impact categories as described on the Help-GEN worksheet. Maintenance Eq. The total piping cost or weight is the sum of results for piping, valves, & fittings. The emission factor is from either EIOLCA or process-based 9see Pipeline Assumptions table) & can be found on the airefs and waterefs worksheet. Emission factors are specific to each impact category.

Material Delivery Calculations for piping, valves, and fittings

Construction Phase Results	The cells calculate the emissions associated with the initial material delivery for system construction for all impact categories and are repeated for each mode. Material Delivery Eq. Piping Wt (kg) = Pipe volume * Matl unit weight AND Valve/Fitting Wt (kg) = No. * Unit wt Weights are entered into the equation shown on the Help-GEN worksheet. The pipe volume is calculated based on dimensions on the Cost-Assump worksheet. Pipe material, fitting, and valve unit weights are also listed on the Cost Assump worksheet.
Maintenance Results	In the summary results, the results for all materials & modes calculated are multiplied by the the Maintenance Factor, as calculated on the DefConv-GI worksheet. Maintenance Eq.

Construction Calculations for piping

Volume Excavated	The volume of soil excavated is calculated in these cells: Exc. Volume (cy) = (Pipe length [ft] * (Pipe Depth + 2 [ft]) * (1.5* Pipe Diameter [ft]))/27 Overexcavation will occur 2 feet elow pipe and 1.5 * Diameter on either side.
Volume Backfilled	The volume of soil backfilled is calculated in these cells: BF Volume (cy) = Exc. Volume (cy) - Pipe Volume (cy)
Volume Offhauled	The volume of soil offhauled is calculated in these cells: OH Volume (cy) = (Exc Volume - BF Volume) * 1.33 The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations for piping

Excavator Use	Excavator use is calculated for both large and small excavator. The large excavator is used for the largest pipe diameter category; the small excavator is used for the other 2 categories. The hours of use are summed for all applications of a particular sized excavator. Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic Excavator output is assumed to be 170 cy/hr for the large excavator. For the small excavator, the bucket width will increase with the size of pipe installed. For a 24" pipe installation, output is 75 cy/hr; for a 10" pipe, 30 cy/hr. The equipment efficiency is defined on the Assumptions-Equipment worksheet; the default value is 60%.
Crane Use	Crane use, for transferring and installing pipe and appurterences, is assumed to be equivalent to large excavator use.
Loader Use	Loader use for backfill is calculated as follows: Loader Use (hr/FU) = BF Volume / Loader Output (cy/hr) * FU / Analysis Pd / Equip Effic Loader output is assumed to be 160 cy/hr. Other factors are previously defined.
Plate Compactor Use	Plate compactor use for backfill within trenches is calculated as follows: PComp Use (hr/FU) = BF Volume / PComp Output (cy/hr) * FU / Analysis Pd / Equip Effic Plate compactor output is 538 cy/hr, assuming a 6 inch lift height and a 1.5 foot plate. Other factors are previously defined.
Dump Truck Use	Dump truck use for offhaul is calculated as follows: DTrk Use (mi/FU) = OH Vol /TrkCap (cy/ld) *OH Dist (mi/ld) *FU *Analysis Pd /Truck Effic Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Manhole and Curb Inlet Calculations are provided for COLLECTION ONLY and are divided by facility (system or WWTP) and material type.

Manholes

Type and dimension	The manhole type (cast-in-place or precast concrete) and the dimensions (depth and inner diameter [ft]) are entered by the user on the ENTRY-COL worksheet. Curb inlet costs and dimensions are default values that can not be changed.
Unit Cost	Manhole and curb inlet costs (1997$) are found on the Cost Assumptions worksheet and depend on the type and dimensions of the manhole or curb inlet.

Cost / FU — Costs are calculated for each facility as follows:
Cost (1997$/FU) = Number of Units * Unit cost * FU / Analysis Pd

% cost / FU — The % Cost is calculated to allocate results to each facility in the calculation and equals:
% Cost / FU = Facility Cost / Sum (Facility Costs)

Material Cost % — The Material Cost % calculates the proportion of costs allocated to different materials depending on the type of manhole or curb inlet. Reinforced concrete costs are split approximately evenly between the steel and concrete components.

Maintenance Multiplier — The Maintenance Factor is calculated on the DefConv-GI worksheet and depends on analysis period and the material service life.

Material Production Calculations

Construction Phase Results — The cells calculate emissions associated with the initial material purchase for construction for all facilities & impact categories, according to the equation on Help-GEN worksheet. Results are later broken back down to the facility level by multiplying by the % cost / FU term. The unit cost is the sum of costs for all facilities. The EF is from EIO-LCA for either precast concrete, rebar, & concrete, as appropriate. Efs are found on the airefs and waterefs worksheets. Emission factors are specific to each impact category. Material Production Eq.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Material Delivery Calculations

Construction Phase Results — The cells calculate emissions associated with initial material delivery for construction for all impact categories & for each mode. The total item cost is the sum of costs for all facilities Material costs & unit weights are on the Cost Assump worksheet. Material Delivery Eq.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
MH Exc. Vol (cy) = (Inner Dia. + 2* WallThick + 4)^2/4*Pi [ft] * (Depth + 2 [ft]) * MH# / 27
CI Exc. Vol (cy) = (L + 2* Wallthick +4)* (W+2*WallThick)* (Depth + 2) [ft] *CI# / 27
Wall thickness is assumed to be 1 ft. It is assumed that overexcation will occur 2 feet below the bottom of the item and 4 feet on the sides.

Volume Backfilled — The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - MH or CI Volume (cy)
MH or CI volume are as shown for volume excavated, without the overexcavation factors.

Volume Offhauled — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations

Excavator Use — Excavator use is calculated for a small excavator. The hours of use are calculated as shown above for piping. Excavator Calc

Crane Use — Crane use, for transferring & installing manholes and curb inlets, is assumed to be equivalent to excavator use.

Loader use, plate compactor use, & dump truck use are similar to piping equations. Equipment Calcs

Pump Calculations are shown for pumps in 3 size categories. Motor capacity is defined on the Entry COL and Entry-DIS worksheets and is transferred directly.

Material Production Calculations Material Production Eq.

Const Cost — Costs are calculated according to the equation shown on the HELP-GENERAL worksheet. Pump costs are given on the Costs Assumptions worksheet and depend on motor capacity.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Material Delivery Calculations Material Delivery Eq.

Construction Phase Results — The cells calculate effects associated with initial material delivery for system construction for all impact categories and for each mode. The equation is on the Help-GENERAL worksheet. Unit weights are found on the Cost Assump worksheet.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Equipment Use Calculations Equipment Use Eq.

Crane Use — Crane use for installing pumps is assumed to be 0.5 hr/pump in the largest size category.

Building and Lift Station Facility Calculations are shown for buildings within all facilities. Station #, average pumps per station, area, wall height, and location (above or below ground) are all transferred from the Assump-COL or ASSUMP-DIS worksheet.

Material Cost Calculations

Concrete Cost — Concrete cost is calculated as follows for an below-ground facility:
Concrete total cost = (Fdtn thickness *Area + √Area *Wall ht *Wall thickness *4) *Stations# *Conc unit cost
If facility is above ground, the wall term is excluded. Dimensions are given in feet; foundation thickness is assumed to be 2.5 ft; wall thickness is assumed to be 1 ft and is defined, along with concrete unit cost in $/cf, on the Cost Assump worksheet.

Steel Cost — Steel cost is calculated as follows:
Steel total cost = Concrete Cost (total) /Conc Unit Cost *Ratio of Steel to Concrete *Steel Unit Cost
Concrete and steel unit costs and the steel to concrete ratio are defined on the Cost Assump worksheet. The ratio of steel to concrete is 0.02 by volume.

Form Cost — Forms cost is calculated as follows for an above-ground facility:
Form total cost = (2 *Area + 2 *4 * √Area *Fdtn thickness) *formcost /formreuse *Stations#
If facility is below ground, the following term is added within the parens:
2 *4 *√Area *Wall height
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

The above equations are adjusted to FU as shown on the Help-GEN worksheet.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated for an aboveground building is calculated in these cells:
Fdtn Exc. Vol (cy) = (√Area +Fdtn Width)^2 *(Fdtn Depth +Fdtn Thickness) *Stations# /27
If the building is below ground, an additional term is added:
(√Area +Fdtn Width)^2 *Wall height
Wall thickness is assumed to be 1 ft. It is assumed that overexcation will occur 2 feet below the bottom and 4 feet on the sides.

Volume Backfilled — The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - Building Volume (cy)
Building volume is calculated as for volume excavated, without the overexcavation factors.

Volume Offhauled — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations — Equipment Use Eq.

Excavator Model — The excavator model is determined based on the total area to be excavated. If the area is greater than 400 sf, a large excavator is used; otherwise, a small excavator is used.

Excavator Use — Excavator use is calculated depending on the model selected. The use hours are calculated as shown above for piping. — Excavator Calc

Loader use & dump truck use are similar to piping equations. — Equipment Calcs

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Material Production Calculations — Material Production Eq.

Const Cost — Costs are calculated according to the equation shown on the HELP-GENERAL worksheet. Construction material costs are calculated as described above.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Other Materials Calculations are shown for all custom-defined materials entered by the user. Life-cycle phase and material are defined by the user on the Entry-COL and Entry-DIS worksheet.

Material Cost Calculations

Cost by facility — The total costs are entered for each facility on the Entry-COL and Entry-DIS worksheet and are converted to a per FU basis as follows:
FU Cost = Total cost * Functional unit /Analysis period * Discount percent
If the purchase is on an annual basis, the analysis period term is ignored. The discount percent is the ratio between the Construction Cost Index for the user-defined purchase year & 1997

Sector — The EIO-LCA or process-based sector is assigned based on the user's material selection.

Material Category — The material category (construction material, equipment, chemical, pipe, fuel, and other) are entered automatically based on the user's material selection. Material categories are assigned for each life-cycle phase.

Material Production Calculations — Material Production Eq.

MP Emissions — Costs are calculated according to the equation shown on the HELP-GENERAL worksheet. Emissions are separated by facility. These results are multiplied by the material category percentage before assigned to a life-cycle phase and material category in the final results.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport. Delivery distances can be edited by the user on the Assump-GEN worksheet. Cargo weight is entered by the user on the Entry-COL and Entry-DIS worksheet.

Electrical and Control Instrumentation Calculations are calculated based on total plant emission costs.
Material Production Calculations Material Production Eq.
For construction phase, electrical equipment is assumed to be 2.8% of total equipment cost. Instrumentation and control equipment is assumed to be 9% of total equipment costs. Electrical calculations use the EIO-LCA sector of Electrical and Industrial Apparatus; controls use the EIO-LCA sector of Relays and Controls.
Maintenance phase results are determined by multiplying construction results by the maintenance factor.
Material Delivery Calculations Material Delivery Eq.
Material delivery calculations are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport. Delivery distances can be edited by the user on the Assump-GEN worksheet. Cargo weight is assumed to be 0.15 kg per $.
Equipment Use Calculations are shown for all custom-defined materials entered by the user. Life-cycle phase, equipment, use schedule, and units are defined by the user on the Entry-COL and Entry-DIS worksheet. Equipment Use Eq.

Annual Use	The total equipment use are entered for each facility on the Entry-COL and Entry-DIS worksheets and are converted to a per FU basis as follows: FU Cost = Total equipment use * Functional unit /Analysis period If use is on an annual basis, the analysis period term is ignored. Results are assigned by facility & life-cycle phase.

CALCULATIONS- LIQUID TREATMENT worksheet

Summary Calculations are divided by facility (system or particular WWTP) and by life-cycle phase (construction, operation, and maintenance). **Material Production** calculations are divided further into material type (construction materials, equipment, chemicals, piping, and other). Results are shown for each of the evaluated chemicals (energy use, GWE,Nox, PM, SOx, VOC, and CO). **Material Delivery** calculations are compiled for different transportation modes (local truck, long distance truck, train, ship, and plane. **Equipment use** is summarized by miles driven or hours used for the different equipment alternatives considered in WWEST. **Fuel consumption** combines information from the material production data entry (fuel materials), material delivery for all modes, and equipment use.
Pipeline Calculations are provided for 2 diameter ranges and pipe lengths entered by the user on the Assump-LTRT worksheet. If no pipe length is entered, the piping is calculated using assumptions from the Cost Assump worksheet, 17% of the total equipment cost for the plant.

Piping	Pipe weight is calculated using the assumed outer diameter for each category, the wall thickness from the Cost Assump worksheets, and pipe length defined by the user or back-calculated based on the default total costs of piping in the plant. The unit weight for plastic pipe is from the Cost Assump worksheet
Valves and Flowmeter	The number of valves and flowmeters are transferred from the ENTRY page and multiplied by the cost from the Cost Assump worksheet.

Material Production Calculations for piping, valves, and fittings

Pipe materials	The cells calculates material production effects for the three diameter categories using the MP equation for process-based lca database (plastics) and EIO-LCA (others) on the Help-GEN worksheet. For EIO-LCA, the unit cost is listed in the Pipeline Assumptions table. (Source: Means 1998). For process-based, the unit weight is calculated in the Pipeline Assumptions table based on data found on the Cost Assump worksheet. Material Production Eq.
Construction Phase Results	The cells calculate emissions associated with the initial material purchase for construction for all impact categories using the Material Production equation. The total piping cost or weight is the sum of results for piping, valves, and fittings. The emission factor (EF) is from EIOLCA or process-based database (see Pipeline Assumptions table) & can be found on the air or water Efs worksheet. EFs are specific to each impact category.
Maintenance Results	The cells calculate emissions associated with subsequent purchases for system maintenance for all impact categories as described on the Help-GEN worksheet. Maintenance Eq. The total piping cost or weight is the sum of results for piping, valves, and fittings. The emission factor is from either EIOLCA or process-based database (see Pipeline Assumptions table) & can be found on the water or air Efs worksheet. EFs are specific to each impact category.

Material Delivery Calculations for piping, valves, and fittings

Construction Phase Results	The cells calculate the emissions associated with the initial material delivery for system construction for all impact categories and are repeated for each mode. Material Delivery Eq. Piping Wt (kg) = Pipe volume * Matl unit weight AND Valve/Fitting Wt (kg) = No. * Unit wt Weights are entered into the equation shown on the Help-GEN worksheet. The pipe volume is calculated based on dimensions on the Cost-Assump worksheet. Pipe material, fitting, and valve unit weights are also listed on the Cost Assump worksheet.
Maintenance Results	In the summary results, the results for all materials and modes calculated are multiplied by the the Maintenance Factor, as calculated on the DefConv-GI worksheet. Maintenance Eq.

Pump Calculations are shown for pumps in 2 size categories and metering pumps. Motor capacity is defined on the Entry-TRT worksheet and is transferred directly.
Material Production Calculations Material Production Eq.

Const Cost	Costs are calculated according to the equation shown on the HELP-GENERAL worksheet. Pump costs are given on the Costs Assumptions worksheet and depend on motor capacity.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Material Delivery Calculations Material Delivery Eq.

Construction Phase Results — The cells calculate emissions associated with initial material delivery for system construction for all impact categories and for each mode. The equation is on the Help-GENERAL worksheet. Unit weights are found on the Cost Assump worksheet.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Equipment Use Calculations Equipment Use Eq.

Crane Use — Crane use for installing large pumps is assumed to be 0.5 hrs/pump in the largest size category.

Annual Chemical Consumption Calculations are shown for all chemicals entered by the user on the Entry-TRT worksheet. Calculations are completed for each facility separately.

EF Source — The source (EIO-LCA or process-based) is assigned automatically based on the type of chemical entered on the Entry-TRT worksheet.

Mass or Cost — Enter mass for chemicals with process-based EF source & cost for EIO-LCA EF source. For EIO-LCA costs, the cost is multiplied by the discount percent (ratio of 1997 construction cost index to the default purchase year's CCI) andthe functional unit. Material Production Eq.

Delivery Distance — The delivery distance and chemical weight, as entered by the user, are multiplied by the functional unit. Material Delivery Eq.

Tank Cost — Tank cost data from the Cost Assump worksheet was analyzed using regression analysis to develop an equation between tank size and cost. Total costs are calculated as follows:

Tank Cost = (101066 *Tank Size /1000000 +34629) *Tank Weight *Functional Unit /Analysis Period

Chemical Calculations Material Production Eq.

Operation phase effects of chemical use are calculated as described on the Entry-GENERAL worksheet. for both material production and material delivery. Material Delivery Eq.

Tank Calculations (Cell BN131)

Foundation dimensions assumptions are provided. Foundation thickness is 2.5 feet and the pad for each tank is 250 sf.

Concrete volume — Concrete volume is the product of area, foundation thickness, and concrete percent, as defined on the Cost Assump worksheets.

Steel volume — Steel volume is calculated by multiplying the concrete volume by the steel percent on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:

Conc cost ($/FU)= Conc volume (cf) /(27cf/cy) *Conc unit cost ($/cy) *Functional Unit /Analysis Period

Concrete unit cost is found on the Cost Assump worksheet.

Steel cost — Steel cost is calculated as follows:

Steel cost ($/FU)= Steel volume (cf) /(27cf/cy) *Steel unit cost ($/cy) *Functional Unit /Analysis Period

Steel unit cost is found on the Cost Assump worksheet.

Form Cost — Forms cost is calculated as follows:

Form cost = (2 *(L +W) *(D +Fdtn thickness) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period

Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Material Production Calculations

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category percentage above before assigned to a life-cycle phase and material category in the final results.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:

Excav Vol (cy) = Tank # *(Fdtn thickness +Fdtn D[ft]) * (Pad side + Fdtn W)^2) /27 ft/cy

Overexcation is assumed to occur 2 feet below the bottom of the item and 4 feet on the sides.

Volume Backfilled — The volume of soil backfilled is calculated in these cells:

BF Volume (cy) = Exc. Volume (cy) - Pad Volume (cy)

Pad volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved — The volume of soil offhauled is calculated in these cells:

OH Volume (cy) = (Exc Volume - BF Volume) * 1.33

The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations for tanks

Excavator Use — Small excavator is used for calculations. The use hours use are summed for all applications.

Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic

For the small excavator, output is 75 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Crane Use — Crane use, for transferring and installing tanks, is assumed to be 1.5 hours per tank.

Loader Use — Loader use for backfill is calculated as follows:

Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic

Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump Truck Use — Dump truck use for offhaul is calculated as follows:
DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Plate Comp. Use — If area is less than 1000 sf,
PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use — If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Other Materials Calculations are shown for all custom-defined materials entered by the user. Life-cycle phase and material are defined by the user on the Entry-TRT worksheet.

Material Cost Calculations

Cost by facility — The total costs are entered for each facility on the Entry-TRT worksheet and are converted to a per FU basis as follows:
FU Cost = Total cost * Functional unit /Analysis period * Discount percent
If the purchase is onannual basis, the analysis period term is ignored. The discount percent is the ratio between the Construction Cost Index for the user-defined purchase year & 1997.

Sector — The EIO-LCA or process-based sector is assigned based on the user's material selection.

Material Category — The material category (construction material, equipment, chemical, pipe, fuel, and other) are entered automatically based on the user's material selection. Material categories are assigned for each life-cycle phase.

Material Production Calculations — Material Production Eq.

MP Emissions — Costs are calculated according to the equation shown on the HELP-GENERAL worksheet. Emissions are separated by facility. These results are multiplied by the material category percentage above before assigned to a life-cycle phase and material category in the final results.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport. Delivery distances can be edited by the user on the Assump-GEN worksheet. Cargo weight is entered by the user on the Entry-TRT worksheet.

Electrical and Control Instrumentation Calculations are calculated based on total plant emission costs.

Material Production Calculations — Material Production Eq.

For construction phase, electrical equipment is assumed to be 2.8% of total equipment cost. Instrumentation and control equipment is assumed to be 9% of total equipment costs. Electrical calculations use the EIO-LCA sector of Electrical and Industrial Apparatus; controls use the EIO-LCA sector of Relays and Controls. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport. Delivery distances can be edited by the user on the Assump-GEN worksheet. Cargo weight is assumed to be 0.15 kg per $.

Equipment Use Calculations are shown for all custom-defined materials entered by the user. Life-cycle phase, equipment, use schedule, and units are defined by the user on the Entry-TRT worksheet.

Equipment Use — The total equipment use are entered for each facility on the Entry-TRT worksheet and are converted to a per FU basis as follows: Equipment Use Eq.
FU Cost = Total equipment use * Functional unit /Analysis period
If use is on an annual basis, the analysis period term is ignored. Results are assigned by facility & life-cycle phase.

PROCESS-SPECIFIC CALCULATIONS

Course Screening Data Calculations are shown to estimate the material production use for bar screening. The first table shows assumptions for the geometry of bar screens. Calculations will be completed only if the user has selected bar screening on the Entry-TRT worksheet.

Bar racks — The default number of racks is assumed to be 2.

Area — The area in sf is calculated as follows:
Area (sf) = Facility flow (cf/s) /Approach velocity (m/s) /Bar racks # *0.305 m/ft

Length/Width — The length is assumed to be 70% of the square root of the area; width is the Area/Length (ft).

Bars # — The number of bars is Width (ft) /12 in per ft *Bar spacing (in)

Steel volume cf — Steel volume is calculated as follows:
Steel volume (cf)= Bars # *Bar Width (in)* Bar depth /(12 in/ft)^2 *Length (ft) *Bar racks#
All bar rack dimensions are included in the dimensions table above.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)= Steel volume (cf) /(27cf/cy) *Steel cost ($/cy) *Functional Unit /Analysis Period
Steel cost is found on the Cost Assump worksheet.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category percentage above before assigned to a life-cycle phase and material category in the final results.

Material Delivery Calculations — Material Delivery Eq.

Steel weight is calculated by dividing steel volume by steel weight. This weight is used in the equation on the Help-GEN worksheet. Delivery distances can be edited by the user on the Assump-GEN worksheet.

Fine/Micro Screening Data Calculations are shown to estimate the material production for other screening. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. Equipment units, cost, and basin dimensions are transferred based on user entry.

Fdtn Thickness — The foundation thickness is assumed to be 0.75 m.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)= Concrete cost ($/FU)/ Concrete Unit Cost ($/m3) *Steel percent *Steel unit cost ($/m3) * Equipment # *Functional Unit /Analysis Period
Concrete cost is calculated in the following column. Concrete and steel unit costs and steel percent are found on the Cost Assump worksheet.

Concrete cost — Concrete cost is calculated as follows:
Concrete cost ($/FU)= ((L *W *Fdtn Thickness [m3]) + ((2 *(L +W) *D [m2]) *Concrete wall thickness [m]))*concrete percent *concrete cost ($/m3) *Equipment # *Functional Unit /Analysis Period
Concrete unit costs and concrete percent are found on the Cost Assump worksheet. Concrete wall thickness is dependant on the depth of the basin and can be edited by the user on the Assump-LTRT worksheet.

Form Cost — Forms cost is calculated as follows:
Form cost = (2 *(L +W) *(D +Fdtn thickness) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Equip # *(Fdtn thcknss+Fdtn D[m]) * (L +Fdtn W) * (W +FdtnW) /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - Pad Volume (cy)
Pad volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator is used for calculations. The use hours use are summed for all applications.
Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic
For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 1 hours per unit.

Loader — Loader use for backfill is calculated as follows:

Use — Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic
Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump Truck Use — Dump truck use for offhaul is calculated as follows:
DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Plate Comp. Use — If area is less than 1000 sf,
PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use — If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Grinding Calculations are shown to estimate the material production for grinding equipment. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. Equipment type, units, cost, material, and basin dimensions are transferred based on user entry.

Equipment Use Calculations — Equipment Use Eq.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 1 hours per unit.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Grit Removal Calculations are shown to estimate the material production for grit removal equipment. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. Plant flowrate, equipment units, chamber type, cost, and basin dimensions are transferred based on user entry. Detention time is calculated for information purposes only. Freeboard is assumed to be 1 foot.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) /(27cf/cy) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)= Steel volume (m3) *Steel unit cost ($/m3) *Functional Unit /Analysis Period
Steel unit cost is found on the Cost Assump worksheet.

Form Cost — Forms cost is calculated as follows:
Form cost = (2 *(L +W) *(D +Fdtn thickness) [m2]) *formcost ($/m2) /formreuse *Equip#

*Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Units # *(Tank Vol /D [m]+ 2* Fdtn W [m]) * (D +Fdtn D) /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W). Foundation thickness is assumed to be 1.5 m.

Volume Backfilled — The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - Tank Volume (cy)
Tank volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations Equipment Use Eq.

Excavator Use — Large excavator is used for calculations. The use hours use are summed for all applications.
Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic
For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 1 hours per unit.

Loader Use — Loader use for backfill is calculated as follows:
Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic
Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump Truck Use — Dump truck use for offhaul is calculated as follows:
DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Plate Comp. Use — If area is less than 1000 sf,
PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use — If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Material Production Calculations Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Flow equalization/Storage Calculations are shown to estimate the material production for storage basins. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet.

A list of assumptions from design literature is provided. Storage capacity, trains #, tank material, aeration and baffling selections, basin dimensions, and mixer and aeration equipment costs are transferred based on user entry. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user. Freeboard is assumed to be 1 foot.

Mixing elect use	Mixing electricity use is calculated as follows when mechanical mixing is used: Elect use (kWh/yr) = Mixing power reqts (kW/m3) *Storage capacity (m3) * Avg filled capacity (%) *24 *365 Mixing power requirements are from Metcalf and Eddy 2003. Average filled capacity is assumed to be 50%.
Steel volume	Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.
Concrete volume	Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.
Soil berm volume	Soil berm volume is calculated when earthen lining is selected. Side slope is assumed to be 3:1 with a top width of 1m. Berm calculations are based on this geometry.
Liner size	Liner size (m2) is calculated when earthen lining is selected. It is the product of area (m2), liner overlap factor (1.2, assumed), and number of basins.
Steel cost	Steel cost is calculated as follows: Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period Steel unit cost is found on the Cost Assump worksheet.
Concrete Cost	Concrete cost is calculated as follows: Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period Concrete unit cost is found on the Cost Assump worksheet.
Form Cost	For a concrete basin, forms cost is calculated as follows: Form cost = (2 *(Area) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.
Equipment cost	Equipment cost is calculated as follows: Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period Discount percent is the ratio between the 1997 and the CCI for the default purchase year.
Liner cost	Liner cost is calculated as follows: Liner cost = Liner area (m2) * Liner unit cost ($/m2) *Function unit /Analysis period Liner unit cost is found on the Cost Assump worksheet.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated	The volume of soil excavated is calculated in these cells: Excav Vol(cy) =Units # *(D + Freeboard +Fdtndepth [m]) *(L +fdtnwidth) *(W +fdtndepth) /0.76 cy/m3 Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).
Volume Backfilled	The volume of soil backfilled is calculated in these cells: BF Volume (cy) = Exc. Volume (cy) - Tank Volume (cy) Tank volume are as shown for volume excavated, without the overexcavation factors.
Volume Moved	The volume of soil offhauled is calculated in these cells: OH Volume (cy) = (Exc Volume - BF Volume) * 1.33 The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations Equipment Use Eq.

Excavator Use	Large excavator is used for calculations. The use hours use are summed for all applications. Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.
Crane Use	Crane use, for transferring and installing equipment, is assumed to be 3 hours per basin.
Loader Use	Loader use for backfill is calculated as follows: Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic Loader output is assumed to be 160 cy/hr. Other factors are previously defined.
Dump Truck Use	Dump truck use for offhaul is calculated as follows: DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.
Plate Comp. Use	If area is less than 1000 sf, PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period

If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use — If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Material Production Calculations Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Rapid Mix Basin Calculations are shown to estimate the material production for rapid mix basins. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. A list of assumptions from design literature is provided. Trains #, tank material, basin dimensions, and mixer equipment costs are transferred based on user entry. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user. Freeboard is assumed to be 1 foot.

Mixing elect use — Mixing electricity use is calculated as follows when mechanical mixing is used:
Elect use (kWh/yr) = (G value [1/s])^2 * Dynamic viscosity (N*s/m2) *Depth (m) *(Side L [m])^2 *Trains # *Mixer utilitization *365 days/yr *24 hrs/day /1000
G value and dynamic viscosity are from Metcalf and Eddy 2003. Mixer utilization is assumed to be 90%.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *(Side L)^2 + 8 *(Side L * [Depth +Freeboard])) *formcost ($/m2) /formreuse *Train# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Trains # *(D + Freeboard +Fdtndepth [m]) *(Side L +fdtnwidth)^2 /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - Tank Volume (cy)
Tank volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator is used for calculations. The use hours use are summed for all applications.
Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic
For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 3 hours per basin.

Loader Use — Loader use calculations are described above.

Dump Truck Use — Dump truck use calculations are described above.

Plate Comp. Use — Plate compactor use calculations are described above.

Roller Comp Use — Roller compactor use calculations are described above.

Concrete Mix Truck — Concrete mix truck use calculations are described above.

Concrete pump — Concrete pump use calculations are described above.

Concrete vibrator — Concrete vibrator use calculations are described above.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Coagulation/Flocculation Calculations are shown to estimate the material production for slow mix basins. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. A list of assumptions from design literature is provided. Trains #, tank material, basin dimensions, type of mixing, and mixer equipment cost and number of units are transferred based on user entry. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user. Freeboard is assumed to be 1 ft.

Mixing elect use — Mixing electricity use is calculated as follows when mechanical mixing is used:
Elect use (kWh/yr) = (G value [1/s])^2 * Dynamic viscosity (N*s/m2) *Depth (m) *(Side L [m])^2 *Trains # *Mixer utilitization *365 days/yr *24 hrs/day /1000
G value and dynamic viscosity are from Metcalf and Eddy 2003. Mixer utilization is assumed to be 90%.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *(Area) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Trains # *(D + Freeboard +Fdtndepth [m]) *(W +fdtnwidth) *(L +fdtnwidth) /0.76 cy/m3

Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled calculations are described above.

Volume Moved — The volume of soil offhauled calculations are described above.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator use calculations are described above.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 1 hours per basin.

Loader Use — Loader usec alculations are described above.

Dump Truck Use — Dump truck use calculations are described above.

Plate Comp. Use — Plate compactor use calculations are described above.

Roller Comp Use — Roller compactor use calculations are described above.

Concrete Mix Truck — Concrete mix truck use calculations are described above.

Concrete pump — Concrete pump use calculations are described above.

Concrete vibrator — Concrete vibrator use calculations are described above.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Sedimentation/Clarification Calculations are shown to estimate the material production for settling basins. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. A list of assumptions from design literature is provided. Trains #, tank material, basin dimensions, and equipment cost and number of units are transferred based on user entry. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user. Freeboard is assumed to be 1 ft.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Steel cost — Steel cost is calculated as follows:

Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period

Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:

Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period

Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:

Form cost = (2 *L*W) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period

Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:

Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period

Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:

Excav Vol(cy) =Trains # *(D + Freeboard +Fdtndepth [m]) *(W +fdtnwidth) *(L +fdtnwidth) /0.76 cy/m3

Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled calculations are described above.

Volume Moved — The volume of soil offhauled calculations are described above.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator use calculations are described above.
Crane Use — Crane use, for transferring and installing equipment, is assumed to be 1 hours per basin.
Loader Use — Loader usec alculations are described above.
Dump Truck Use — Dump truck use calculations are described above.
Plate Comp. Use — Plate compactor use calculations are described above.
Roller Comp Use — Roller compactor use calculations are described above.
Concrete Mix Truck — Concrete mix truck use calculations are described above.
Concrete pump — Concrete pump use calculations are described above.
Concrete vibrator — Concrete vibrator use calculations are described above.

Material Production Calculations Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Conventional Filtration Calculations are shown to estimate the material production for depth filters. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. Trains #, tank material and shape, medium depths, basin dimensions, and equipment cost are transferred based on user entry. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user. Freeboard is assumed to be 1 ft.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.
Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.
Medium volume — Media volume for selected media (sand, anthracite, garnet, and gravel) is calculated based on user-defined depths and basin geometry.
Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.
Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.
Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *L*W) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.
Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.
Media cost — Media costs are calculated using total volumes and unit costs from the Cost Assump work-sheet. Sand, gravel, and garnet sand are grouped into one category.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Trains # *(D + Freeboard +Fdtndepth [m]) *(W +fdtnwidth) *(L +fdtnwidth) /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).
Volume Backfilled — The volume of soil backfilled calculations are described above.
Volume Moved — The volume of soil offhauled calculations are described above.

Equipment Use Calculations Equipment Use Eq.

Excavator Use — Large excavator use calculations are described above.
Crane Use — Crane use, for transferring and installing equipment, is assumed to be 1 hours per basin.

Loader Use — Loader usec alculations are described above.
Dump Truck Use — Dump truck use calculations are described above.
Plate Comp. Use — Plate compactor use calculations are described above.
Roller Comp Use — Roller compactor use calculations are described above.
Concrete Mix Truck — Concrete mix truck use calculations are described above.
Concrete pump — Concrete pump use calculations are described above.
Concrete vibrator — Concrete vibrator use calculations are described above.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Sand, gravel, and garnet sand are included in the Sand and Gravel EIO-LCA sector, anthracite is part of the coal sector, and synthetic media is categorized within the packing and sealing devices sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Membrane Filtration Calculations are shown to estimate the material production for membrane systems. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. Trains #, membrane type, material and number, membrane cost, and electricity consumption are transferred based on user entry.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; thin-film/PSU, PPE and PAN membranes are in the EIO-LCA sector Plastic Materials and Resins; cellulose acetate membranes are categorized into the Cellulosic organic fiber manufacturing in EIO-LCA. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Activated Sludge (AS) Calculations are shown to estimate the material production for AS systems. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. Trains #, AS type, tank material, shape, and dimensions for both AS and nutrient removal, and equipment cost are transferred based on user entry. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user. Freeboard is assumed to be 1 ft. Tank is assumed to be square.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *L*W) + 8 *(Side L *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Calculaton is completed for both AS and nutrient removal tanks. Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Trains # *(D + Freeboard +Fdtndepth [m]) *(Side L +fdtnwidth)^2 /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume — The volume of soil backfilled calculations are described above.

Volume Backfilled Moved — The volume of soil offhauled calculations are described above.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator use calculations are described above.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 2 hours per AS or nutrient removal tank.

Loader Use — Loader usec alculations are described above.

Dump Truck Use — Dump truck use calculations are described above.

Plate Comp. Use — Plate compactor use calculations are described above.

Roller Comp Use — Roller compactor use calculations are described above.

Concrete Mix Truck — Concrete mix truck use calculations are described above.

Concrete pump — Concrete pump use calculations are described above.

Concrete vibrator — Concrete vibrator use calculations are described above.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Ponds / Lagoons Calculations are shown to estimate the material production for pond and similar systems. Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. Up to 2 different types of ponds can be entterred on each line. Ponds type and #, dimensions, and liner, biogas cover, and equipment cost are transferred based on user entry for each type of pond selected.

Liner Cost — Costs for pond liners and biogas covers are grouped together, multiplied vy fuctional unit and discount percent (defined in Equipment costs)and divided by time period.

Equipment cost — Equipment cost is calculated as follows:

Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period

Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

No Material Delivery Calculations are included for Ponds and Lagoons.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells. For each pond type defined:

Excav Vol(cy) =Trains # *(D + Freeboard +Fdtndepth [m]) *(L +fdtnwidth) *(W +fdtnwidth) /0.76 cy/m3

Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled calculations are described above.

Volume Moved — The volume of soil offhauled calculations are described above.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator use calculations are described above.

Loader Use — Loader usec alculations are described above.

Dump Truck Use — Dump truck use calculations are described above.

Plate Comp. Use — Plate compactor use calculations are described above.

Roller Comp Use — Roller compactor use calculations are described above.

Concrete Mix Truck — Concrete mix truck use calculations are described above.

Concrete pump — Concrete pump use calculations are described above.

Concrete vibrator — Concrete vibrator use calculations are described above.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; liners use the EIO-LCA sector Plastic

Materials and Resins.

Carbon Adsorption Calculations are shown to estimate the material production for carbon systems.
Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet.
Trains #, carbon type,number of vessels, tank volume, carbon cost and average life, & equipment cost are are transferred based on user entry.

Material Production Calculations Material Production Eq.

Carbon Cost — Carbon cost is calculated as:
Carbon cost = Train# * *Vessel # *Carbon Cost *Discount percent *Functional Unit /Analysis Period

Tank Cost — Tank costs are calculated as carbon costs but the equation for indicivdual tank cost is from the regression analysis on the Cost Assumption worksheet that relates tank volume and cost.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; activated carbon is part of Other misc. chemical EILOCA sector; tanks are from the Iron and steel forgings EIO-LCA sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Disinfection Calculations are shown to estimate the effects of disinfection systems. Multiple options are available: chlorine-based chemicals, ozone, and ultraviolet light (UV; not available). Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet. For chlorine-based disinfection, chemical & declorination information, basins #, basin dimensions & equipment costs for both chlorination & dechlorination basins are transferred based on user entry. For ozone disinfection, ozone use, basin #, contact basin dimensions, equipment cost, and electricity use & transferred based on user entry. Wall thickness is defined on the Assump-LTRT sheet & can be edited. Freeboard is assumed to be 1 ft.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *L*W) + 8 *(Side L *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Calculaton is completed for both AS and nutrient removal tanks. Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Basins # *(D + Freeboard +Fdtndepth [m]) *(W +fdtnwidth) *(L +fdtnwidth) /0.76 cy/m3
For chlorine-based disinfection, the volume is calculated for both chorination and dechlorination basins. Overexcation is assumed to occur 2 ft below the bottom of the item (Fdtn D) and 4 ft on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled calculations are described above.

Volume Moved — The volume of soil offhauled calculations are described above.

Equipment Use Calculations Equipment Use Eq.

Excavator Use — Large excavator use calculations are described above.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 2 hours per basin.

Loader Use — Loader usec alculations are described above.

Dump Truck Use — Dump truck use calculations are described above.

Plate Comp. Use — Plate compactor use calculations are described above.
Roller Comp Use — Roller compactor use calculations are described above.
Concrete Mix Truck — Concrete mix truck use calculations are described above.
Concrete pump — Concrete pump use calculations are described above.
Concrete vibrator — Concrete vibrator use calculations are described above.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

CALCULATIONS- SLUDGE TREATMENT worksheet

Summary Calculations are divided by facility (system or particular WWTP) and by life-cycle phase (construction, operation, and maintenance). **Material Production** calculations are divided further into material type (construction materials, equipment, chemicals, piping, and other). Results are shown for each of the evaluated chemicals (energy use, GWE,Nox, PM, SOx, VOC, and CO). **Material Delivery** calculations are compiled for different transportation modes (local truck, long distance truck, train, ship, and plane. **Equipment use** is summarized by miles driven or hours used for the different equipment alternatives considered in WWEST. **Fuel consumption** combines information from the material production data entry (fuel materials), materual delivery for all modes, and equipment use.

Pipeline Calculations are provided for 2 diameter ranges and pipe lengths entered by the user on the Assump-TRT worksheet. If no pipe length is entered, the piping is calculated using assumptions from the Cost Assump worksheet, 17% of the total equipment cost for the plant.

Piping — Pipe weight is calculated using the assumed outer diameter for each category, the wall thickness from the Cost Assump worksheets, and pipe length defined by the user or back-calculated based on the default total costs of piping in the plant. The unit weight for plastic pipe is from the Cost Assump worksheet

Valves and Flowmeter — The number of valves and flowmeters are transferred from the ENTRY page and multiplied by the cost from the Cost Assump worksheet.

Material Production Calculations for piping, valves, and fittings

Pipe materials — The cells calculates material production effects for the three diameter categories using the Material Production equation for process-based efs (plastics) on the Help-GEN worksheet. The unit weight is calculated in the Pipeline Assumptions table based on data found on the Cost Assump worksheet. Material Production Eq.

Construction Phase Results — The cells calculate emissions associated with the initial material purchase for construction for all impact categories using the Material Production equation.
The total piping cost or weight is the sum of results for piping, valves, and fittings. The emission factor (EF) is from EIOLCA or process-based database (see Pipeline Assumptions table) & can be found on the airefs and waterefs worksheets. Emission factors are specific to each impact category.

Maintenance Results — The cells calculate emissions associated with subsequent purchases for system maintenance for all impact categories as described on the Help-GEN worksheet. Maintenance Eq.
The total piping cost or weight is the sum of results for piping, valves, and fittings. The emission factor is from either EIOLCA or process-based database (see Pipeline Assumptions table) & can be found on the airefs and waterefs worksheet. Emission factors are specific to each impact category. The

Material Delivery Calculations for piping, valves, and fittings

Construction Phase Results — The cells calculate the emissions associated with the initial material delivery for system construction for all impact categories and are repeated for each mode. Material Delivery Eq.
Piping Wt (kg) = Pipe volume * Matl unit weight AND Valve/Fitting Wt (kg) = No. * Unit wt
Weights are entered into the equation shown on the Help-GEN worksheet.
The pipe volume is calculated based on dimensions on the Cost-Assump worksheet. Pipe material, fitting, and valve unit weights are also listed on the Cost Assump worksheet.

Maintenance Results — In the summary results, the results for all materials and modes calculated are multiplied by the the Maintenance Factor, as calculated on the DefConv-GI worksheet. Maintenance Eq.

Pump Calculations are shown for pumps in 2 size categories and metering pumps. Motor capacity is defined on the Entry worksheets and is transferred directly.

Material Production Calculations — Material Production Eq.

Const Cost — Costs are calculated according to the equation shown on the HELP-GENERAL worksheet. Pump costs are given on the Costs Assumptions worksheet and depend on motor capacity.
Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Material Delivery Calculations — Material Delivery Eq.

Construction — The cells calculate emissions associated with initial material delivery for system construction for

Phase Results — all impact categories and for each mode. The equation is on the Help-GENERAL worksheet. Unit weights are found on the Cost Assump worksheet.

Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Equipment Use Calculations Equipment Use Eq.

Crane Use — Crane use for installing large pumps is assumed to be 0.5 hrs/pump in the largest size category.

Annual Chemical Consumption Calculations are shown for all chemicals entered by the user on the Entry-TRT worksheet. Calculations are completed for each facility separately.

EF Source — The EF source (EIO-LCA or process-based) is assigned based on the type of chemical entered on the Entry-TRT worksheet.

Mass or Cost — Enter as mass for chemicals with process-based EF source and cost for EIO-LCA EF source. For EIO-LCA costs, the cost is multiplied by the discount percent (ratio of 1997 construction cost index to the default purchase year's CCI) andthe functional unit. Material Production Eq.

Delivery Distance — The delivery distance and chemical weight, as entered by the user, are multiplied by the functional unit. Material Delivery Eq.

Tank Cost — Tank cost data from the Cost Assump worksheet was analyzed using regression analysis to develop an equation between tank size and cost. Total costs are calculated as follows:

Tank Cost = (101066 *Tank Size /1000000 +34629) *Tank Weight *Functional Unit /Analysis Period

Chemical Calculations Material Production Eq.

Operation phase effects of chemical use are calculated as described on the Entry-GENERAL worksheet. for both material production and material delivery. Material Delivery Eq.

Tank Calculations (Cell BN131)

Foundation dimensions assumptions are provided. Foundation thickness is 2.5 feet and the pad for each tank is 250 sf.

Concrete volume — Concrete volume is the product of area, foundation thickness, and concrete percent, as defined on the Cost Assump worksheets.

Steel volume — Steel volume is calculated by multiplying the concrete volume by the steel percent on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:

Steel cost ($/FU)= Steel volume (cf) /(27cf/cy) *Steel cost ($/cy) *Functional Unit /Analysis Period

Steel cost is found on the Cost Assump worksheet.

Steel cost — Steel cost is calculated as follows:

Steel cost ($/FU)= Steel volume (cf) /(27cf/cy) *Steel cost ($/cy) *Functional Unit /Analysis Period

Steel cost is found on the Cost Assump worksheet.

Form Cost — Forms cost is calculated as follows:

Form cost = (2 *(L +W) *(D +Fdtn thickness) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period

Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Material Production Calculations

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category percentage above before assigned to a life-cycle phase and material category in the final results.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:

Excav Vol (cy) = Tank # *(Fdtn thickness +Fdtn D[ft]) * (Pad side + Fdtn W)^2) /27 ft/cy

Overexcation is assumed to occur 2 feet below the bottom of the item and 4 feet on the sides.

Volume Backfilled — The volume of soil backfilled is calculated in these cells:

BF Volume (cy) = Exc. Volume (cy) - Pad Volume (cy)

Pad volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved — The volume of soil offhauled is calculated in these cells:

OH Volume (cy) = (Exc Volume - BF Volume) * 1.33

The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations for tanks

Excavator Use — Small excavator is used for calculations. The use hours use are summed for all applications.

Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic

For the small excavator, output is 75 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Crane Use — Crane use, for transferring and installing tanks, is assumed to be 1.5 hours per tank.

Loader Use — Loader use for backfill is calculated as follows:

Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic

Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump — Dump truck use for offhaul is calculated as follows:

Truck Use — DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Plate Comp. Use — If area is less than 1000 sf,
PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use — If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Other Materials Calculations are shown for all custom-defined materials entered by the user. Life-cycle phase and material are defined by the user on the Entry-TRTworksheet.

Material Cost Calculations

Cost by facility — The total costs are entered for each facility on the Entry-TRT worksheet and are converted to a per FU basis as follows:
FU Cost = Total cost * Functional unit /Analysis period * Discount percent
If the purchase is on an annual basis, the analysis period term is ignored. The discount percent is the ratio between the Construction Cost Index for the user-defined purchase year & 1997.

Sector — The EIO-LCA or process-based sector is assigned based on the user's material selection.

Material Category — The material category (construction material, equipment, chemical, pipe, fuel, and other) are entered automatically based on the user's material selection. Material categories are assigned for each life-cycle phase.

Material Production Calculations — Material Production Eq.

MP Emissions — Costs are calculated according to the equation shown on the HELP-GENERAL worksheet. Emissions are separated by facility. These results are multiplied by the material category percentage above before assigned to a life-cycle phase and material category in the final results.

Material Delivery Calculations — Material Delivery Eq.

Material delivery effects are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport. Delivery distances can be edited by the user on the Assump-GEN worksheet. Cargo weight is entered by the user on the Entry-TRT worksheet.

Electrical and Control Instrumentation Calculations are calculated based on total plant emission costs.

Material Production Calculations — Material Production Eq.

For construction phase, electrical equipment is assumed to be 2.8% of total equipment cost. Instrumentation and control equipment is assumed to be 9% of total equipment costs. Electrical calculations use the EIO-LCA sector of Electrical and Industrial Apparatus; controls use the EIO-LCA sector of Relays and Controls.
Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport. Delivery distances can be edited by the user on the Assump-GEN worksheet. Cargo weight is assumed to be 0.15 kg per $.

Equipment Use Calculations are shown for all custom-defined materials entered by the user. Life-cycle phase, equipment, use schedule, and units are defined by the user on the Entry-TRT worksheet.

Equipment Use — The total equipment use are entered for each facility on the Entry-TRT worksheet and are converted to a per FU basis as follows: — Equipment Use Eq.
FU Cost = Total equipment use * Functional unit /Analysis period
If use is on an annual basis, the analysis period term is ignored. Results are assigned by facility & life-cycle phase.

PROCESS-SPECIFIC CALCULATIONS

Grinding Calculations are shown to estimate the material production for grinding equipment.
Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet.
Equipment type, units, cost, and basin dimensions are transferred based on user entry.

Equipment Use Calculations Equipment Use Eq.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 1 hours per unit.

Material Production Calculations Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Storage Calculations are shown to estimate the material production for storage basins.
Calculations will be completed only if the user selects this treatment process on the Entry-TRT sheet.
A list of assumptions from design literature is provided. Storage capacity, trains #, tank material, aeration and baffling selections, basin dimensions, and mixer and aeration equipment costs are transferred based on user entry. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user.
Freeboard is assumed to be 1 foot.

Mixing elect use — Mixing electricity use is calculated as follows when mechanical mixing is used:
Elect use (kWh/yr) = Mixing power reqts (kW/m3) *Storage capacity (m3) * Avg filled capacity (%) *24 *365
Mixing power requirements are from Metcalf and Eddy 2003. Average filled capacity is assumed to be 50%.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Soil berm volume — Soil berm volume is calculated when earthen lining is selected. Side slope is assumed to be 3:1 with a top width of 1m. Berm calculations are based on this geometry.

Liner size — Liner size (m2) is calculated when earthen lining is selected. It is the product of area (m2), liner overlap factor (1.2, assumed), and number of basins.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *(Area) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Liner cost — Liner cost is calculated as follows:
Liner cost = Liner area (m2) * Liner unit cost ($/m2) *Function unit /Analysis period
Liner unit cost is found on the Cost Assump worksheet.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Units # *(D + Freeboard +Fdtndepth [m]) *(L +fdtnwidth) *(W +fdtndepth) /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - Tank Volume (cy)
Tank volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations Equipment Use Eq.

Excavator Use — Large excavator is used for calculations. The use hours use are summed for all applications.
Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic
For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Crane Use — Crane use, for transferring and installing equipment, is assumed to be 3 hours per basin.

Loader Use — Loader use for backfill is calculated as follows:
Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic
Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump Truck Use — Dump truck use for offhaul is calculated as follows:
DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Plate Comp. Use — If area is less than 1000 sf,
PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use — If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Material Production Calculations Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

THICKENING/DEWATERING CALCULATIONS are described in three categories: mechanical, gravity-based, and beds or lagoons. Each category is described separately below.

Mechanical Thickening/Dewatering Calculations are shown to estimate the material production for belt/filter presses, centrifuges, rotary drum, thermal drying. Calculations will be completed only if the user selects this process on the Entry-TRT sheet. Equipment number, type, cost and hours of use are transferred based on user entry. Freeboard is assumed to be 1 ft. Wall thickness is defined on the Assump-LTRT worksheet & can be edited by the user.

Equipment Use Calculations

Crane Use — Crane equipment use is assumed to be one hour per piece of equipment. Equipment Use Eq.

Gravity Thickening/Dewatering Calculations are shown to estimate the material production for gravity thickening and flotation processes. Calculations will be completed only if the user selects this process on the Entry-TRT sheet. Thickener number, equipment options, tank material and dimensions, and costs are transferred based on user entry. Freeboard is assumed to be 1 ft. Wall thickness is defined on the Assump-LTRT worksheet and can be edited by the user.

Steel volume — Steel volume is calculated based on basin type, basin material, and dimensions. Steel tanks calculations use wall thickness defined on the Assump-LTRT worksheet. For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined on the Assump-LTRT worksheet.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:

Form cost = (2 *(Area) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost
Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated
The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Units # *(D + Freeboard +Fdtndepth [m]) *(L +fdtnwidth) *(W +fdtndepth) /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled
The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - Tank Volume (cy)
Tank volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved
The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations Equipment Use Eq.

Excavator Use
Large excavator is used for calculations. The use hours use are summed for all applications.
Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic
For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Loader Use
Loader use for backfill is calculated as follows:
Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic
Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump Truck Use
Dump truck use for offhaul is calculated as follows:
DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Plate Comp. Use
If area is less than 1000 sf,
PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use
If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck
Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period
Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump
Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator
Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Material Production Calculations Material Production Eq.

MP Emissions
Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Drying Bed or Lagoon Calculations estimate the emissions associated with these dewatering processes.

Calculations will be completed only if the user selects this process on the Entry-TRT sheet. Default assumptions from literature are shown. Bed type, bed number, bed foundation and wall materials, cleaning method, mixing, bed dimensions, and equipment costs are transferred based on user entry.

Steel volume — For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined above.

Asphalt volume — Asphalt volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined above.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *(Area) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Asphalt cost — Asphalt volume is calculated similar to concrete cost but uses the asphalt volume and unit costs from Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
Excav Vol(cy) =Units # *(D + Freeboard +Fdtndepth [m]) *(L +fdtnwidth) *(W +fdtndepth) /0.76 cy/m3
Overexcation is assumed to occur 2 feet below the bottom of the item (Fdtn D) and 4 feet on the sides (Fdtn W).

Volume Backfilled — The volume of soil backfilled is calculated in these cells:
BF Volume (cy) = Exc. Volume (cy) - Tank Volume (cy)
Tank volume are as shown for volume excavated, without the overexcavation factors.

Volume Moved — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator is used for calculations. The use hours use are summed for all applications.
Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic
For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Loader Use — Loader use for backfill is calculated as follows:
Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic
Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump Truck Use — Dump truck use for offhaul is calculated as follows:
DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default value is 80%.

Plate Comp. Use — If area is less than 1000 sf,
PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.

Roller Comp Use — If area is larger than 1000 sf,
Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period
It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.

Concrete Mix Truck — Concrete mix truck use is calculated as follows:
Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period

Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete pump — Concrete pump use is calculated as follows:
Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period
Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Concrete vibrator — Concrete vibrator use is calculated as follows:
Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period
Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.

Material Production Calculations — Material Production Eq.

MP Emissions — Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Stabilization Calculations estimate the emissions associated with these treatment processes. Calculations will be completed only if the user selects this process on the Entry-TRT sheet. Default assumptions are shown. Technology type, train number, tank dimensions, and equipment costs are transferred based on user entry. Wall thickness is defined on the Assump-LTRT page.

Steel volume — For concrete tanks, steel is calculated as a percent of concrete volume as defined on Cost Assump worksheet.

Concrete volume — Concrete volume is calculated based on basin type, basin material, and dimensions. Calculations use wall thickness defined above.

Steel cost — Steel cost is calculated as follows:
Steel cost ($/FU)=Steel volume (m3) *Steel unit cost ($/m3) *Functional unit /Analysis period
Steel unit cost is found on the Cost Assump worksheet.

Concrete Cost — Concrete cost is calculated as follows:
Conc cost ($/FU)= Conc volume (m3) *Conc unit cost ($/m3) *Functional Unit /Analysis Period
Concrete unit cost is found on the Cost Assump worksheet.

Form Cost — For a concrete basin, forms cost is calculated as follows:
Form cost = (2 *(Area) + 4 *(L *D) +4 *(W *D) [m2]) *formcost ($/m2) /formreuse *Equip# *Functional unit /Analysis Period
Form cost and form reuse (assumed to be 3) are defined on the Cost Assump worksheet.

Equipment cost — Equipment cost is calculated as follows:
Equipment cost = Equipment# * Equipment Cost *Discount percent *Functional Unit /Analysis Period
Discount percent is the ratio between the 1997 and the CCI for the default purchase year.

Material Delivery Calculations — Material Delivery Eq.

Material delivery calculations for rebar and forms are calculated according to the equation on the Help-GEN worksheet for up to two modes of transport.

Construction Calculations

Volume Excavated — The volume of soil excavated is calculated in these cells:
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Volume Moved — The volume of soil offhauled is calculated in these cells:
OH Volume (cy) = (Exc Volume - BF Volume) * 1.33
The factor 1.33 represents the fluff factor of excavated soil.

Equipment Use Calculations — Equipment Use Eq.

Excavator Use — Large excavator is used for calculations. The use hours use are summed for all applications.
Excvtr Use (hr/FU) = Exc Vol (cy) / Exc Output (cy/hr) *FU / Analysis Pd / Equip Effic
For the large excavator, output is 170 cy/hr. Equipment efficiency is defined on the Assump-Equipment worksheet; the default value is 60%.

Loader Use — Loader use for backfill is calculated as follows:
Loader Use (hr/FU) = (BF Vol +Moved Vol) /Ldr Output (cy/hr) *FU /Analysis Pd /Equip Effic
Loader output is assumed to be 160 cy/hr. Other factors are previously defined.

Dump Truck Use — Dump truck use for offhaul is calculated as follows:
DTrk Use (mi/FU) = OH Vol / TrkCap (cy/ld) * OH Dist (mi/ld) * FU * Analysis Pd / Truck Effic
Truck capacity is assumed to be 15 cy/load (ld). Offhaul distaince is assumed to be 30 miles round-trip. Truck efficiency is defined on the Assumptions-Equipment worksheet; the default

	value is 80%.
Plate Comp. Use	If area is less than 1000 sf, PC Use (hr/FU) = Backfill Vol (cy) /PC Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period If area is larger than 1000 sf, it is assumed that 500 cy will be compacted with a plate compacter and the remainder with a roller compactor. PC output is found on EQ Data worksheet and equals 538 cy per hour.
Roller Comp Use	If area is larger than 1000 sf, Roller Use (hr/FU) = (Backfill Vol -500 [cy]) /Roller Output (cy/hr) *Functional Unit *Equip Efficiency /Analysis Period It is assumed that 500 cy will be compacted with a plate compactor. Roller output is defined on the EU data worksheet and equals 550 cy/hr.
Concrete Mix Truck	Concrete mix truck use is calculated as follows: Concrete Trck Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete truck capacity * Functional Unit /Truck Efficiency /Analysis Period Truck capacity (15 cy) is found on the EU data worksheet. Truck efficiency is defined & can be edited on the Assump-EQUIP worksheet. Other terms are defined elsewhere.
Concrete pump	Concrete pump use is calculated as follows: Concrete Pump Use (hr) = Concrete total cost /Concrete unit cost /Concrete pump capacity * Functional Unit /Equipment Efficiency /Analysis Period Concrete pump capacity (40 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.
Concrete vibrator	Concrete vibrator use is calculated as follows: Concrete Vibrator Use (hr) = Concrete Total Cost /Concrete Unit Cost /Concrete vibrator output * Functional Unit /Truck Efficiency /Analysis Period Concrete vibrator output (27 cy/hr) is defined on the EU data worksheet. Equipment efficiency is defined on the Assump-EQUIP worksheet. Other terms are defined elsewhere.
Material Production Calculations	Material Production Eq.
MP Emissions	Emissions are calculated according to the equation shown on the HELP-GENERAL worksheet and are separated by facility. These results are multiplied by the material category. Equipment uses EIO-LCA sector General Inustrial Equipment; concrete- ready-mixed concrete sector; rebar- blast furnace and steel mill sector, and forms- sawmills sector. Maintenance phase results are determined by multiplying construction results by the maintenance factor.

Sludge Disposal Calcs- To be finished

HELP- RESULTS worksheets

Jump to HELP Topic:

Results- DATA
Results- GRAPHS
Results- ENERGY PRODUCTION
Results- COLLECTION/DISCHARGE
Results- LIQUID TREATMENT/SLUDGE TREATMENT

Return to:

Entry- General
Results- Graphs

Jump to Addditonal HELP worksheets:

Help- GENERAL
Help- ENTRY
Help- CALCULATIONS
Help- REFERENCES

RESULTS- Data

Key to Abbreviations	This table defines the abbreviations used on this page. It is less complete than the abbreviations list on the Help-GENERAL worksheet. Go to full abbreviations list.
Table 1: Summary Results	This table provides summary results for each category of facilities, wastewater phase, life-cycle phase, and activity. The results, except for facility results, are averaged over the total production of water included in the tool, i.e., it includes production of system and non-system sources. The contribution of each category to the overall results is also presented as a percentage.
Table 2: Detailed Results	This table provides summary results for broken down for the facilities, wastewater phase, life-cycle phase, and activity. These results can be summed according to the user's desires and needs on a separate worksheet.

RESULTS- Graphs

Summary results in terms of emission mass per functional unit (as defined by the user) are illustrated in the first 3 graphs (energy summary, GWE summary, and other air emission summary. In the last four graphs, the contribution of each facility, wastewater phase, life-cycle phase, and activity to the overall results. The user can create additional graphs using the detailed results on the Results-Data worksheet, as desired.

RESULTS- Energy Production

Table EP-1: Summary Results	This table provides summary results for each category of facilities, wastewater phase, life-cycle phase, and activity. The results, except for facility results, are summed over the total production of water included in the tool, i.e., it includes production of system and non-system sources. The contribution of each category to the overall results is also presented as a percentage
Table EP-2 Detailed EP Results	This table provides summary results for broken down for the facilities, wastewater phase, life-cycle phase, and activity. Results for different fuel sources (total, electricity and natural gas production, and fuel production) are shown in separate sections.

RESULTS- Collection/Discharge **Results- COL** **Results- DIS**

The results in this table are summarized based on calculations on the Calcs-COL and Calcs-DIS worksheets. In this table, the results from the calculation worksheets are normalized by the wastewater production volume for each of the different facilities. All results are broken down by life-cycle phase (construction, operation, and maintenance).

Material Production	The results for material production are shown by material category (construction materials, equipment, chemicals,piping, other, and total).	COL	DIS
Material Delivery	The results for material delivery are calculated by summing the products of transport units per functional unit (kg*km/FU; as calculated on the Calcs-COL and Calcs-DIS worksheets) by the emissions factors on the MD Efs worksheets. Plane calculations include separate terms for flight and landing/takeoff.	COL	DIS
Equipment Use	The results for equipment use are calculated by summing the products of equipment use units (in hours or miles, as calculated on the Calcs-COL and Calcs-DIS worksheets) by the appropriate emission factor for each equipment type. The emission factors are defined, and can be edited by the user, on the Assump-EQUIP worksheet.	COL	DIS
Fuel Production	Fuel production results are calculated by summing the products of the fuel costs ($/FU; as calculated on the Calcs-COL and Calcs-DIS worksheets) associated with material delivery, equipment use, and other material entry on the Entry-COL and Entry-DIS worksheets by the EIO-LCA EFs found on the airefs and waterefs worksheet.	COL	DIS

RESULTS- Liquid Treatment/ Sludge Treatment **Results- LTRT** **Results- STRT**

The results in this table are summarized based on calculations on the Calcs-LTRT and Calcs-STRT worksheets. In this table, the results from the calculation worksheets are normalized by the wastewater production volume for each of the different facilities. All results are broken down by life-cycle phase (construction, operation, maintenance, and, for sludge treatment only, end-of-life).

Material Production	The results for material production are shown by material category (construction materials, equipment, chemicals,piping, other, and total).	LTRT	STRT
Material Delivery	The results for material delivery are calculated by summing the products of transport units per functional unit (kg*km/FU; as calculated on the Calcs-LTRT and Calcs-STRT worksheets) by the emissions factors on the MD Efs worksheets. Plane calculations include separate terms for flight and landing/takeoff.	LTRT	STRT
Equipment Use	The results for equipment use are calculated by summing the products of equipment use units (in hours or miles, as calculated on the Calcs-LTRT and Calcs-STRT worksheets) by the appropriate emission factor for each equipment type. The emission factors are defined, and can be edited by the user, on the Assump-EQUIP worksheet.	LTRT	STRT
Fuel Production	Fuel production results are calculated by summing the products of the fuel costs ($/FU; as calculated on the Calcs-LTRT and Calcs-STRT worksheets) associated with material delivery, equipment use, and other material entry on the Entry-LTRT and Entry-STRT worksheets by the EIO-LCA EF found on the airefs and waterefs worksheet.	LTRT	STRT
Direct GHG	The results for direct emissions of GHG (methane and nitrous oxides) are transferred directly from the Calcs-LTRT and Calcs-STRT worksheets.	LTRT	STRT
Sludge Disposal	Sludge treatment only. Sludge disposal calculations are transferred directly from the Calcs-STRT worksheet & are assigned to the EOL life-cycle phase.		STRT

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- Mels, A. R.; van Nieuwenhuijzen, A. F.; van der Graaf, J.; Klapwijk, B.; de Koning, J.; Rulkens, W. H., Sustainability criteria as a tool in the development of new sewage treatment methods. Water Science and Technology 1999, 39, (5), 243-250.
- Monteith, H. D.; Sahely, H. R.; MacLean, H. L.; Bagley, D. M., A rational procedure for estimation of greenhouse-gas emissions from municipal wastewater treatment plants. Water Environment Research 2005, 77, (4), 390-403.
- Palme, U.; Lundin, M.; Tillman, A. M.; Molander, S., Sustainable development indicators for wastewater systems - researchers and indicator users in a co-operative case study. Resources Conservation and Recycling 2005, 43, (3), 293-311.

Appendix B

Appendix B.1.: Publications

Appendix B.2.: Presentations

Appendix B.1: Publications

The following are citations for the publications associated with this research. Due to copyright restrictions, the full text of these papers 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). This article is still In Print but may be found at: http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000036

Appendix B.2: Presentations

Appendix B.2.1: C. Facanha and J. Stokes (2007). “Sustainability of Infrastructure Systems” Chinese Institute of Engineers Conference, San Jose, Calif., February 11 1

Appendix B.2.2: J. Stokes (2007). “Energy Use and Greenhouse Gas Emissions of Water and Wastewater Services: A Life-cycle View” American Water Works Association (AWWA) California-Nevada Section Conference, Sacramento, Calif., April 24. 11

Appendix B.2.3: J. Stokes (2007). “Life-cycle Environmental Evaluation of California Water Supply” Society for Environmental Toxicology and Chemistry- North America Annual Conference, Milwaukee, Wisc., November 12. 17

Appendix B.2.4: J. Stokes (2007). “The Life cycle Climate Change Contributions of Water Systems” Peninsula AWWA Meeting, December 5. 21

Appendix B.2.5: 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. 27

Appendix B.2.6: J. Stokes (2009). “A Cradle-to-Cradle Assessment of Energy and Climate Change Impacts of Recycled Water”, WateReuse California Section Conference, San Francisco, California, March 23.] 32

Appendix B.2.1:
Sustainability of Infrastructure Systems

C. Facanha and J. Stokes (2007). “Sustainability of Infrastructure Systems” Chinese Institute of Engineers Conference, San Jose, Calif., February 11

Sustainability of Infrastructure Systems:

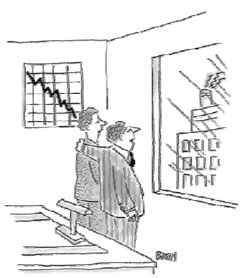
What is does that mean?
What can we as engineers do about it?
How can we evaluate it?

Dr. Cristiano Facanha
ICF International
and
Dr. Jennifer Stokes
University of California Berkeley
Department of Civil and Environmental Engineering

Chinese Institute of Engineers Conference
February 11, 2007

Where Are We?

SF Chronicle, 01/04/02



"Someday, son, none of this will be yours."

Cartoon by Aaron Bacall

Where Are We Heading?

Nepszabadsag, 8/21/01

Part 1
Sustainability:
What is it and why do we care?

The Grand Vision: Sustainable Development

- Definition: Meeting the needs of the current generation without sacrificing the ability of the future generations to meet their needs. (Brundtland Commission, 1987)
- Myriad alternative processes, materials, designs
  - Need to examine the environmental implications of each
    - Need to ask relevant questions and come up with metrics
    - Need to assess a broad range of environmental effects
  - Need economy-wide, life-cycle perspective
  - Need *progress*, not *growth*

Why Problematic

- Why is depletion of natural resources an issue?
  - Directly related to air pollution and waste
    - Especially GHG, criteria pollutant and toxic emissions from fuel burning for energy
  - Actual and potential source of conflicts
  - “Unethical” towards future generations
  - Not sustainable

  etc.

- Consumption related to population growth

What Are Our Goals?

- Maintain societal progress while improving environmental quality and quality of life
- Environmental goals
  - reduce non-renewable resource use
  - manage renewable resource use for sustainability
  - reduce toxic substance emissions (heavy metals, solvents, ozone depleting substances)
  - reduce greenhouse gas (GHG) emissions
- Educate the stakeholders
- Do good by doing well
  - profit = revenue - cost

Part 2
What can we as engineers do about it?

First, make sure we understand the problem…

Characteristics of Engineered Systems

- Products and processes
- Manufacturing and service
- Complicated!
- Globalized!
- Need energy!

www.nepszabadsag.hu, December 18, 2003

www.nepszabadsag.hu, March 12, 2003

Material Flows in the U.S.

- A total of 2.8 billion Mg of different materials used in the U.S. in 1995 (USGS)
  - 81% by volume were construction materials, mostly stone, sand and gravel
- 25% of virgin wood demand by construction (World Watch Institute, 1995)
- In the U.S., buildings account for
  - 65% of electricity consumption
  - 30% of GHG emissions
  - 30% of raw material use
  - 30% of waste output
  - 12% of potable water consumption
- 12 billion Mg of concrete used annually worldwide
- Apparent flows substantial
- Non-apparent flows are even larger

State of Infrastructure

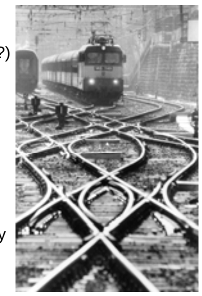
- Necessary for economic development of a country
  - Cement as measure of economic progress
- Many in the world lack access to infrastructure
- Substandard, overloaded infrastructure even in developing countries
- Considered “underfunded”, “in bad shape” (ASCE Report Card 1998, 2001, 2005)
- Real maintenance needs typically neglected worldwide
- Constant, quantitative and qualitative growth

Characteristics of Civil Systems

- Products and processes
- Manufacturing and service
- Long service lifetimes
- Slower obsolescence (?) compared to industrial products
- Large, complicated, in the public eye
- Decisions have significant economic, environmental and social consequences

What Will Influence the Growth of Civil Systems?

- Growth in (primarily urban) population
  - 6.1 billion people in 2001, 7 billion projected for 2030 (but perhaps not?)
  - 95% of growth projected in "developing countries"
- Growth in "middle class"
  - about 2 billion people today
  - Growing in China (now ~50M) and India
- Water shortages
  - projected to affect 3 billion people by 2015
- Longer life span, but aging population
- Information technology



www.nepszabadsag.hu, January 20, 2000

Triple Bottom Line for Sustainability of Infrastructure

- Environmental: natural systems, public health
- Economic: job creation, investments, taxes, public and private services
- Social: safety, equity, civil rights, justice, security, …

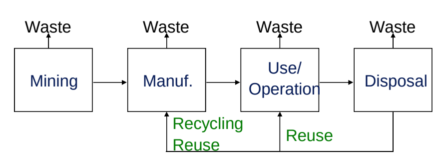
Part 3
How do we evaluate it?

Life-cycle Assessment: An Overview

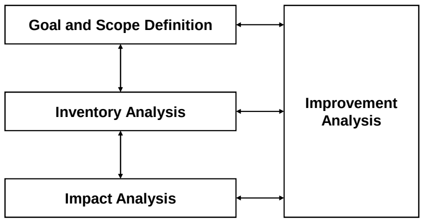
http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

Life-cycle Assessment (LCA)

- A concept and methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the whole life cycle of a particular product, process, or activity (U.S. EPA, 1993).
- LCA studies analyze the environmental aspects and potential impacts throughout a product's life cycle (e.g., cradle-to-grave) from raw material acquisition through production, use and disposal (ISO).

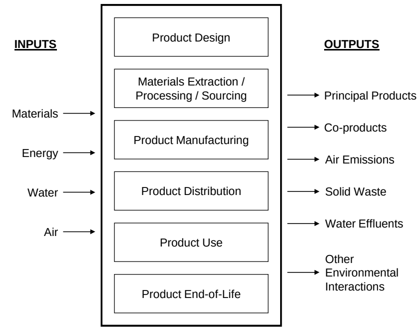


LCA Methodology – ISO 14040



Source: Graedel (2003)

LCA Framework

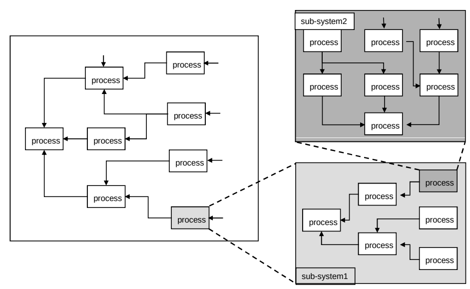


Source: Adapted from SETAC (1991)

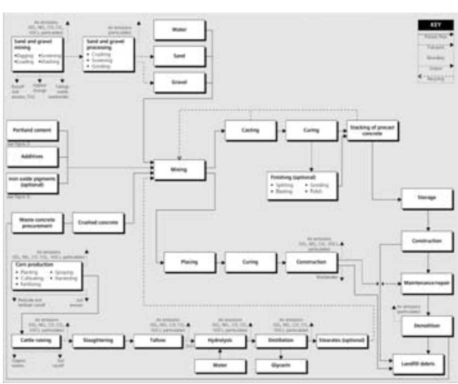
LCA Models

- Process-based LCA, developed by SETAC, EPA, and ISO, based on unit process models, process flow diagrams
  - Primary basis for ISO 14000 standards
  - Goal is to include all processes but can be limited by time or financial resources
- Economic input-output analysis-based LCA (EIO-LCA)
  - Developed by Carnegie Mellon University's Green Design Initiative
  - Boundary is by definition the entire economy, recognizing interrelationships among industrial sectors

Structure of a Process-based LCA Model



Process Flow of Cement Concrete



AIA, "Environmental Resource Guide," John Wiley & Sons, 1997

Life-cycle Assessment
An Example

Appendix B.2.1 4

LCA: Paper vs. Plastic Cups?

- Trees are, in theory, a renewable resource
- Plastic comes from fossil fuels
- Both use chemicals and energy in the manufacturing process that may harm the environment
  - But which uses more?
- Both can be recycled
  - But does recycling occur more frequently for one than the other?
  - If they aren't recycled, what happens to them?

Paper Vs. Plastic Cups: Comparison of Two Studies

	Hocking	EIO-LCA	Hocking	EIO-LCA
	Plastic	Plastic	Paper	Paper
Electricity [kWh]	20-30	2,630	980	5,150
Air emissions [kg]	7-8	10	18-28	19

Functional Unit: 100,000 cups

Hocking, M. B. (1991), "Paper versus Polystyrene: A Complex Choice." *Science*, Vol. 251, February 1, pp. 504-505.

Lave, L. B., E. Cobas, C. Hendrickson and F. C. McMichael, "Using Input-Output Analysis to Estimate Economy-Wide Discharges," *Environmental Science and Technology*, 29(9), pp. 153-161, September 1995.

Life-cycle Assessment
A Hands-on Exercise

Example: CD vs. Paper

- Conference proceedings
  - New: CD
  - Old: 200 pages per person
- Which alternative is better in terms of environmental performance?
  1. What are the steps necessary to complete your life-cycle analysis?
  2. Which questions would you need to ask?
  3. What are the main factors that are contribute to the environmental performance of both alternatives?

Steps for Life-cycle Analysis

- Problem definition
- Magnitude of the problem
- Scope of assessment
- Functional unit
- Boundary of assessment
- Time horizon of the problem
- Process mapping
- Inputs and outputs of the system
- Fate and transport of pollution
- Impact of pollution on environment

- Iterative process, not linear!

Potential Questions

- Production
  - What materials are products made of?
  - How are they manufactured? What materials are used? How much energy is consumed during manufacturing? What are the effects of the waste?
  - How would you compare the printing process (paper) to the burning process (CD) in terms of material and energy?
- Use
  - What is the difference in the way they are used by the conference attendees in the future?
- End-of-Life
  - What happens to each at the end of its life? Are they recyclable?

Economic Effects - Two options

Production Only

Paper

Sector	$
Pulp mills	3,120
Logging	500
Industrial chem's	400
Wholesale trade	260
Sawmills	230
Forestry products	150
Crude petroleum	140
Trucking services	130
Electric utilities	130

CDs

Sector	$
Mag. Media	1,500
Misc. plastics	250
Wholesale trade	170
Plastics	110
Industrial chem's	80
Trucking services	70
Elec. Component	60
Paper mills	50
Electric utilities	50

Environmental Effects

Pollutant (lbs)	Paper	CD
SO2	35	2
Particulates	10	0.1
Global Warming Potential	3000	600
TRI Chemicals	20	2

LCA: The Pros and Cons

PROS:
- Generally, LCA:
  - Provides economic and environmental information about products, processes or systems that is currently unavailable
  - Includes Information about the whole life-cycle, and relationships between life-cycle phases
  - Quantifies impacts of products and processes on flora and fauna
- Companies can:
  - Understand environmental implications of products/processes
  - Identify and minimize sources of pollution and waste
  - evaluate environmental performance
- Others can compare two competing alternatives to see how the environmental effects compare

CONS:
- Lack of comprehensive and reliable data
- Can be expensive and slow
- Defining problem boundaries for LCA is controversial and arbitrary.
- No single LCA method is universally agreed upon and acceptable.
- Published LCA studies typically document only a few impacts.
- Equally credible analyses can produce qualitatively different results; the results of any particular LCA cannot be defended scientifically.
- LCA cannot capture the dynamics of changing markets and technologies.

LCA in Construction

- Assess the entire life-cycle of a product to establish materials intensity/environmental effect.
  - Include the life-cycle stages + the infrastructure to service the product.
- Extend the boundary of the assessment to direct, as well as indirect resource inputs and environmental outputs.
  - Indirect effects include circularity effects: e.g., need steel to produce steel.

Construction Product Comparisons

- Need to compare
  - equivalent designs where functionality delivers equal benefits
  - life-cycle costs, not just first costs
  - service life/longevity/durability (the role of obsolescence and technological change)
- Valuation of environmental burdens depend on risk, perception, and public policy choices

Environmental Implications of Design Choice

- Asphalt vs. concrete pavements
- Steel vs. reinforced concrete highway bridges
- Steel vs. reinforced concrete vs. plastic resin foot bridges
- Wood vs. steel frame residential housing
- Reinforced concrete vs. steel frame commercial building
- Concrete vs. plastic vs. steel vs. iron pipes

End-of-Life Options for Construction Products

- Reuse (e.g., concrete traffic barriers moved to new location)
- Recycling into equivalent new application (e.g., asphalt recycling)
- Recycling into lower value use (post-consumer plastic made into roadside appurtenances; shredded tires (crumb rubber) used in pavements)
- Incineration (e.g., cement kilns fueled with used tires)
- Landfilling (as with much construction debris)
- Direct release into the environment (e.g., cement dumped on the ground)

Case Study
Water Supply Alternatives in California

Why We Care about Water?

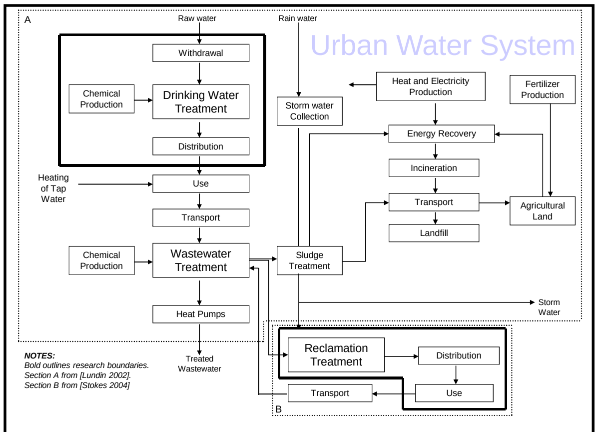
- Capital spending for water infrastructure construction is estimated to be $154 - 446 billion between 2000 and 2019 [EPA 2002]
- 2-3% of global and U.S. energy consumption is used for water and wastewater services; will grow by 33% in the next 20 years [ASE 2002]
- Pumping water is the largest use of electricity in California (7%) [MMWD 2001]

AND YET…

- One-third of the world lives in nations experiencing water shortages; need 25% more water in the next century to meet global demand [World Bank 2001]
- Eight western states have "substantial" or "high" probability of water shortages by 2025; "highly likely" that coastal California cities will experience water shortages by 2025 [USDOI 2003]
- No comprehensive study of the environmental effects of U.S. urban water systems has been conducted…

Research Objectives

- To create a *model* which identifies and inventories inputs to and outputs from urban water supply systems
- To quantify the *environmental effects* of these systems
- To develop a *tool* to assist interested parties in assessing the environmental effects of their water supply decisions
- To compare water supply *alternatives* in California, especially importing, desalinating, and recycling water



Summary of Components Considered

- Energy consumption
- Material delivery
- Construction processes (e.g., site preparation, earthwork, excavation, and concrete placement)
- Pipes, valves, valve boxes, flowmeters, and fittings
- Pumps and motors
- Electrical and control equipment
- Buildings and structures
- Dams for reservoirs
- Extraction wells
- Chemicals
- Filter media
- Treatment equipment (e.g., flocculation paddles, filters, RO membranes)
- Sludge disposal
- Water tanks

Analysis Summary

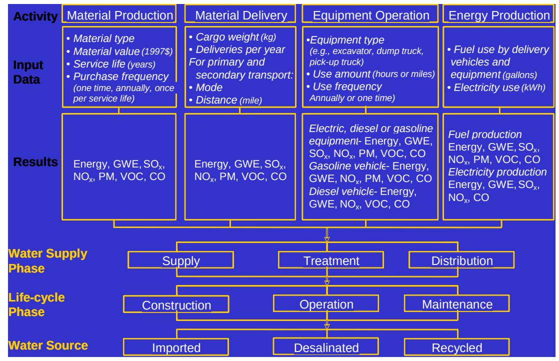
Functional Unit: 100 acre-feet (123 million liters)

Analysis Period: 100 years

Environmental Effects Considered:

- Energy consumption
- Emissions: Greenhouse gases: (N_2O, CH_4, CO_2), Certain criteria air pollutants (SO_x, NO_2, PM, CO), Volatile organic compounds (VOC)
- Global impacts: Global warming effect

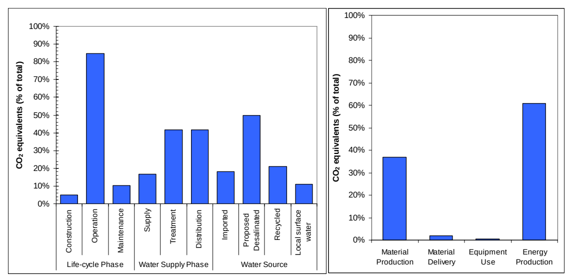
WEST Structure



MMWD Case Study

- Marin Municipal Water District
- Service area: 147 square miles
- Population: approximately 200,000
- Annual Rainfall: 30-50" annually
- Water sources
  - 76% local surface water
  - 22% imported from Russian River
  - May replace imported water with desalinated water from San Francisco Bay
  - 2% recycled water

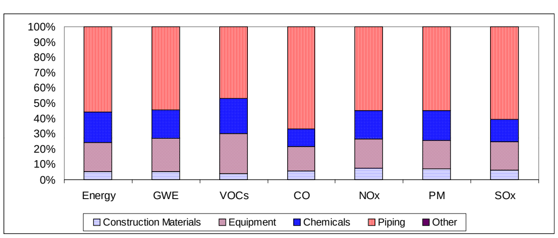
MMWD's Global Warming Effect Results



Results for 100 AF of water from each source

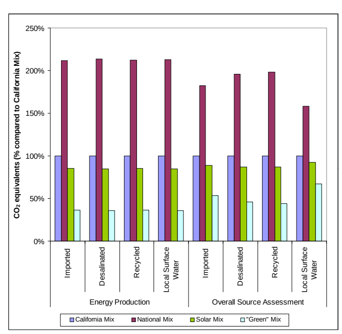
Results for 100 AF of water from the system

Material Production Results



Results for 100 AF of water from each source

Desalinated Water with Alternative Energy Sources



	California Mix	National Mix	Solar Mix	"Green" Mix
Ca. Mix	--	--	50%	20%
Coal	1.1	51.7%	0%	0%
Oil	1.4	2.8%	0%	0%
Natural Gas	49.6	15.9%	0%	0%
Nuclear	16.9	19.8%	0%	20%
Other fossil fuels	1.5	0.6%	0%	0%
Hydro	18.8	7.1%	0%	0%
Wind	1.7	20.0%	0%	15%
Solar	0.3	0.0%	50%	20%
Geo-thermal	5.9	0.4%	0%	10%

Other Results Available

- What are the environmental emissions associated with the system's water supply mix?
- Which activity contributes most to the results (material production, material delivery, equipment use, and energy production)?
- How are results affected if alternative (e.g., "green") electricity is used?
- Which inputs most affect the final results?

Conclusions

Key Results

- If OWD results are typical, an estimated 15 million MWh of electricity are used to provide urban water in California (20% of 2002 electricity); 4 million Mg of CO_2 equivalents are emitted.
- Desalination creates the most environmental effects; if desalination were used to provide Metropolitan Water District's water, 8% of 2002 electricity would be used to process it.
- Results are largely case-specific.
- Operation phase is key for all water sources.
- For imported water, supply phase dominates; for desalination, treatment; for recycled water, distribution.
- Electricity generation produces most effects, followed by material production.

Recommendations

- Incorporate LCA into long-term water supply planning process, such as Urban Water Management Plans.
- Use results to inform federal funding for water programs.
- Conduct analyses of additional water systems to determine what most affects results.
- Encourage water systems to more closely track material and energy use in systems.
- Reassess desalination results as technology improves.
- Encourage supply chain improvements for materials that substantially affect results (RO membranes, pipe, and sand and gravel).

Thanks to…

- National Science Foundation Graduate Fellowship Program
- University of California Toxic Substances Research and Teaching Fellowship
- California Energy Commission Public Interest Energy Research Grant –Environmental Area [Contract Number 500-02-004]

The remaining slides related to Dr. Facanha's research were deleted. These were not Energy Commission funded.

Appendix B.2.2:
Life-cycle Climate Change Effects of Water Supply Systems

J. Stokes (2007). “Energy Use and Greenhouse Gas Emissions of Water and Wastewater Services: A Life-cycle View” American Water Works Association (AWWA) California-Nevada Section Conference, Sacramento, Calif., April 24. .

Energy Use and Greenhouse Gas Emissions of Water & Wastewater Services: A Life-cycle View

Jennifer Stokes, Ph.D.
Arpad Horvath, Associate Professor
University of California, Berkeley
Department of Civil and Environmental Engineering
Consortium on Green Design and Manufacturing
(cgdm.berkeley.edu)

April 24, 2007
AWWA California-Nevada Conference

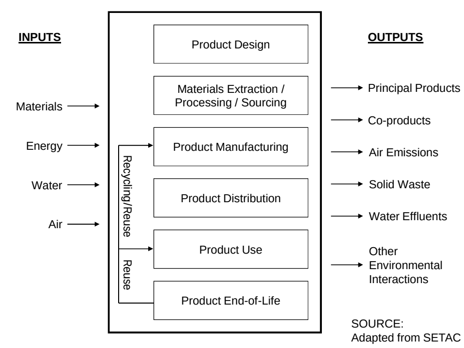
Introduction to Life-cycle Assessment

A Primer on the Method

http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

Method – Significance – WEST – Results – Conclusions

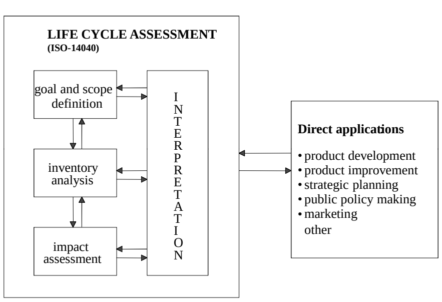
LCA Framework



SOURCE:
Adapted from SETAC (1991)

Method – Significance – WEST – Results – Conclusions

Life-cycle Assessment Process (ISO 14040)



Method – Significance – WEST – Results – Conclusions

Why use LCA?

- To quantify the material/energy consumption of processes in the system
- To quantify the environmental emissions associated with system construction, operation and maintenance
- To consider the effects of the supply chain, get a big-picture assessment
- To compare design alternatives
- To identify where improvements can be made in system design or operation

Method – Significance – WEST – Results – Conclusions

Research Significance

What is the big deal about water, infrastructure, and the environment, anyway?

Water Systems Contribute to Climate Change

- Energy Consumption
  - 2-3% of global energy is used for water and wastewater services
  - Energy use will grow by 33% in next 20 years [ASE 2002]
- Infrastructure Construction and Maintenance
  - Capital spending for water infrastructure is estimated to be $154 - 446 billion between 2000 and 2019 [EPA 2002]
  - Generally, construction produces 38% of greenhouse gas emissions [Wilson 2001]

Method – **Significance** – WEST – Results – Conclusions

Global Warming Solutions Act (AB-32)

- Long-term goal: 80% below 1990 GHG emission levels by 2050
- Mandatory reporting process/combustion emissions and energy purchases coming soon
- Focus on eight strategies to achieve half the goal, potentially includes some POTWs
- Creates environment where assessing GHG emissions in planning decisions is encouraged statewide (carbon trading program?)

Method – **Significance** – WEST – Results – Conclusions

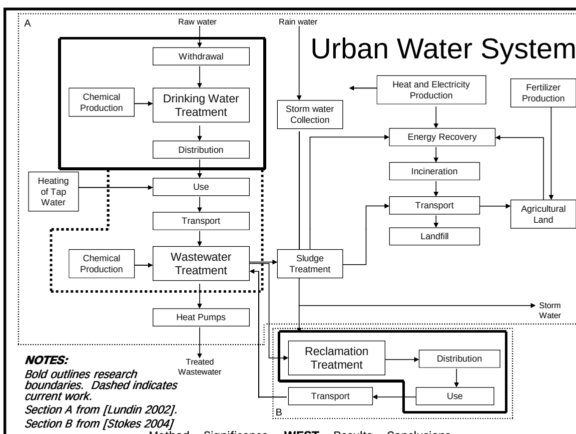
The Water-Energy Sustainability Tool (WEST)

A Research Overview

Research Objectives

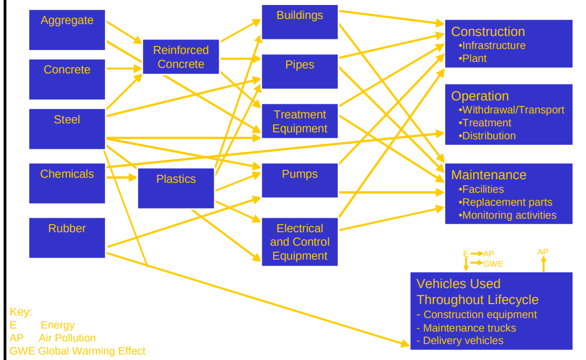
- Create a *model* to identify and inventory inputs to and outputs from water systems over the life-cycle
- Quantify the *environmental effects* of these systems (energy use, greenhouse gas emissions, air emissions)
- Develop a *tool* to assist interested parties in assessing the environmental effects of their water supply decisions using current and potential energy mixes
- Compare supply *alternatives* with California case studies

Method – Significance – **WEST** – Results – Conclusions



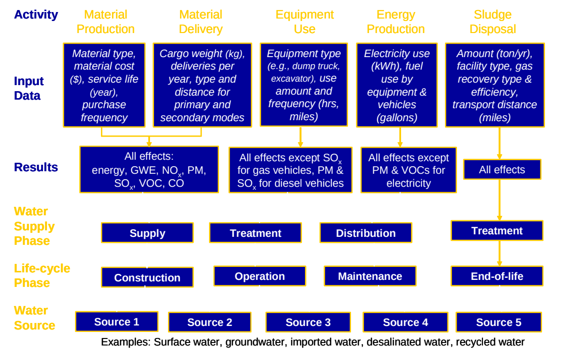
Method – Significance – **WEST** – Results – Conclusions

Process Diagram for Water Supply



Method – Significance – **WEST** – Results – Conclusions

WEST Structure



Method – Significance – **WEST** – Results – Conclusions

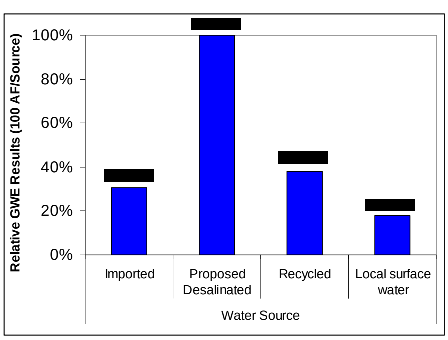
Results

MMWD Case Study

- Marin Municipal Water District
- Service area: 147 square miles
- Population: approximately 200,000
- Water sources
  - 76% local surface water
  - 22% imported from Russian River
  - May replace imported water with desalinated water from San Francisco Bay
  - 2% recycled water
- Analyzed production of 100 AF of water annually for a 100 year period

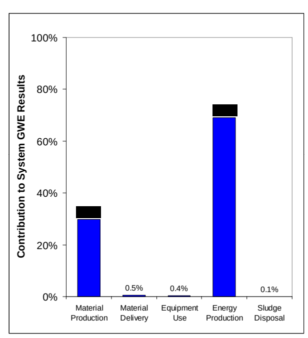
Method – Significance – WEST – **Results** – Conclusions

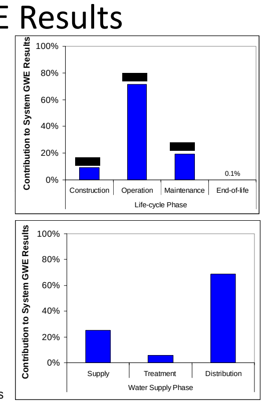
Global Warming Effect Results



Method – Significance – WEST – **Results** – Conclusions

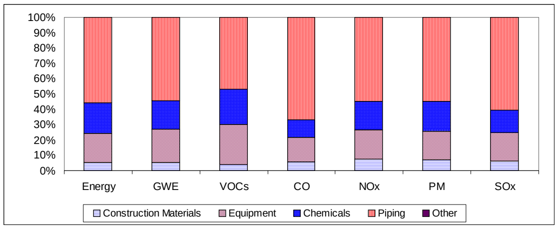
System GWE Results





Method – Significance – WEST – **Results** – Conclusions

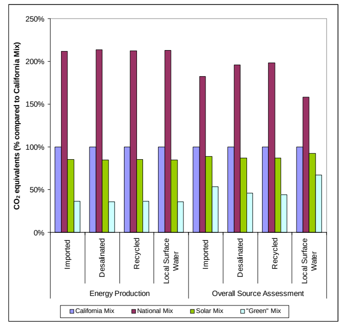
Material Production Results



Results for 100 AF of water from each source

Method – Significance – WEST – **Results** – Conclusions

Desalinated Water with Alternative Energy Sources



	California Mix	National Mix	Solar Mix	"Green" Mix
Ca. Mix	--	--	50%	20%
Coal	1.1	51.7%	0%	0%
Oil	1.4	2.8%	0%	0%
Natural Gas	49.6	15.9%	0%	0%
Nuclear	16.9	19.8%	0%	20%
Other fossil fuels	1.5	0.6%	0%	0%
Hydro	18.8	7.1%	0%	0%
Wind	1.7	20.0%	0%	15%
Solar	0.3	0.0%	50%	20%
Geo-thermal	5.9	0.4%	0%	10%

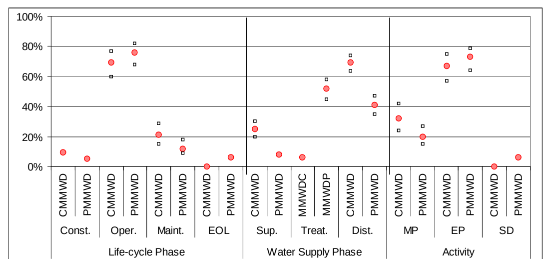
Method – Significance – WEST – **Results** – Conclusions

Sensitivity

- The Usual Suspects:
  - Consumer water demand
  - Proportion of water from each source
  - Electricity consumption and emission factors
- Some surprises:
  - Costs and production emission factors for metal and concrete piping and appurterences
  - Chemical production emission factors
  - Control equipment service life
  - Sludge disposal volume and emission factors

Method – Significance – WEST – **Results** – Conclusions

Uncertainty



CMMWD = Current System with imported water
PMMWD = Proposed System with desalination
Notes: Circles indicate median results. Small boxes bound the 10th to 90th percentile.

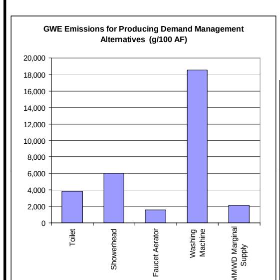
Method – Significance – WEST – **Results** – Conclusions

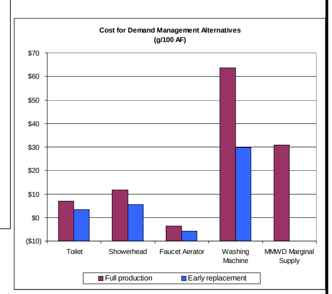
Conserving Water

- Compared conserving and supplying an equivalent volume of water.
- Evaluate GWE and full cost savings using a variety of water efficient household devices
- Includes emissions from manufacturing equipment, associated economic and environmental costs, and economic and environmental costs for avoided water and energy costs

Method – Significance – WEST – **Results** – Conclusions

Water Conservation Results





Method – Significance – WEST – **Results** – Conclusions

Conclusions

Key Results

- Conservation is preferable to supplying water.
- Producing desalinated water for MWD (Southern California) would consume more than 13% of the state's current electricity consumption, assuming MMWD technology.
- Operation phase is key. For desalination, treatment phase dominates; for imported water, supply; for recycled water, distribution.
- Electricity generation produces most effects (>60%), followed by material production (>35%).
- Results are largely case-specific and are sensitive to electricity use and emission factors, volume of water produced, and emission factors for material production (e.g., RO membranes, piping).

Method – Significance – WEST – Results – **Conclusions**

Recommendations

- Incorporate LCA into long-term water supply planning process, such as Urban Water Management Plans.
- Use results to inform federal funding for water programs.
- Conduct analyses of additional water systems to determine what most affects results.
- Encourage water systems to more closely track material and energy use in systems.
- Reassess desalination results as technology improves.
- Encourage supply chain improvements for materials that substantially affect results (RO membranes, pipe, and sand and gravel).

Method – Significance – WEST – Results – **Conclusions**

About the future…

- Work will continue through Dec 2009.
- We are seeking partner case study utilities to gain more data.
- We are planning a series of workshops to introduce WEST to the industry; anticipated in 2008.
- We will develop a partner tool to assess wastewater systems.
- We plan to incorporate other environmental effects (discharges to water and land).

Method – Significance – WEST – Results – **Conclusions**

Thanks to…

- National Science Foundation Graduate Fellowship Program
- University of California Toxic Substances Research and Teaching Fellowship
- California Energy Commission Public Interest Energy Research Grant –Environmental Area [Contract Number 500-02-004]

For more information

- http://www.ce.berkeley.edu/~horvath/west.html
- jrstokes@cal.berkeley.edu

Appendix B.2.3:
Life-cycle Environmental Evaluation of California Water Supply

J. Stokes (2007). “Life-cycle Environmental Evaluation of California Water Supply” Society for Environmental Toxicology and Chemistry- North America Annual Conference, Milwaukee, Wisc., November 12.

Life-Cycle
Environmental Evaluation of California Water Supply

Jennifer Stokes, Ph.D.
Arpad Horvath, Associate Professor
University of California, Berkeley
Department of Civil and Environmental Engineering
Consortium on Green Design and Manufacturing
(cgdm.berkeley.edu)

November 12, 2007
SETAC- North America, Milwaukee

http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

Method – Significance – WEST – Results – Conclusions

Research Significance

What is the big deal about water, infrastructure, and the environment, anyway?

Water Systems and the Environment

- Infrastructure
  - Capital spending for water infrastructure is estimated to be $154 - 446 billion between 2000 and 2019 [EPA 2002]
  - Generally, construction produces 38% of greenhouse gas emissions [Wilson 2001]
- Energy Consumption
  - 2-3% of global energy is used for water and wastewater services
  - Energy use will grow by 33% in next 20 years [ASE 2002]
- May be targeted by California's Climate Change Initiative (AB-32)

Method – **Significance** – WEST – Results – Conclusions

The Water-Energy Sustainability Tool (WEST)

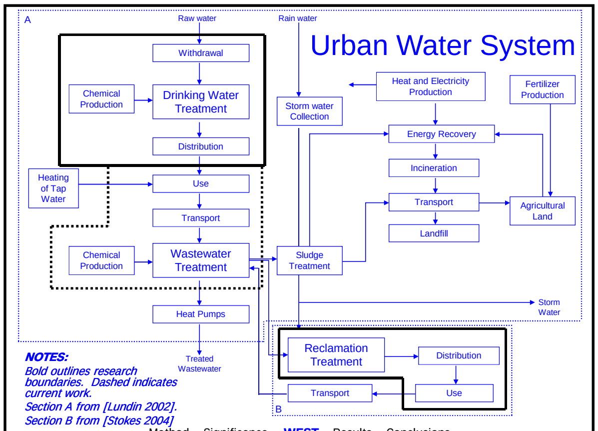
A Research Overview

Research Objectives

- Create a *model* to identify & inventory inputs to & outputs from systems over the life-cycle
- Quantify the *environmental effects* of these systems (energy use, greenhouse gas and other air emissions)
- Develop a *tool* to assist others in assessing the environmental effects of their water supply decisions
- Compare supply *alternatives* using California case studies

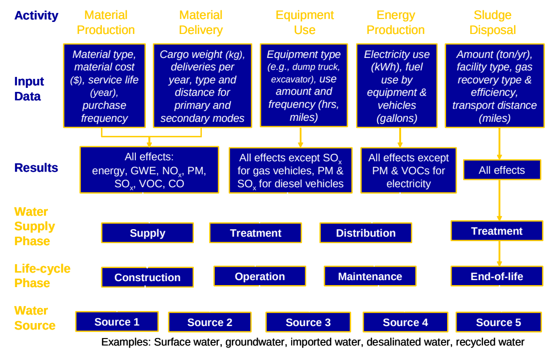
Method – Significance – **WEST** – Results – Conclusions

Urban Water System



Method – Significance – **WEST** – Results – Conclusions

WEST Structure



Method – Significance – **WEST** – Results – Conclusions

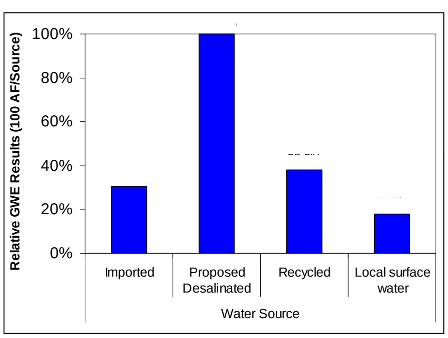
Results

Case Study

- Marin Municipal Water District in San Francisco Bay Area
- Serves ~200,000 people over 147 square miles
- Water sources
  - 76% local surface water
  - 22% imported from Russian River
  - May replace imported water with desalinated water
  - 2% recycled water
- Analyzed production of 100 AF of water annually for a 100 year period

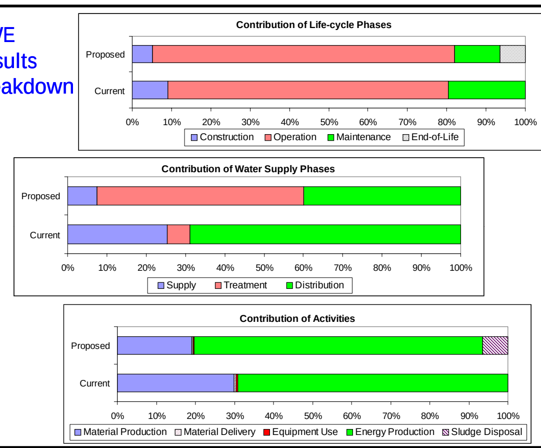
Method – Significance – WEST – **Results** – Conclusions

Global Warming Effect Results

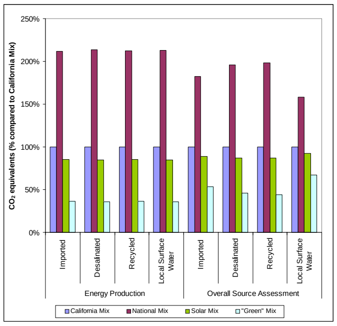


Method – Significance – WEST – **Results** – Conclusions

GWE Results Breakdown



Supplying Water with Alternative Energy



	California Mix	National Mix	Solar Mix	"Green" Mix
Ca. Mix	--	--	50%	20%
Coal	1.1	51.7%	0%	0%
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Other fossil fuels	1.5	0.6%	0%	0%
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Wind	1.7	20.0%	0%	15%
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Method – Significance – WEST – **Results** – Conclusions

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Method – Significance – WEST – **Results** – Conclusions

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- We can't rely on desalination. Producing desalinated water for MWD (Southern California) would consume more than 13% of the state's current electricity consumption, assuming MMWD technology.
- Using solar power would not substantially lower GHG emissions below the California energy mix.
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Method – Significance – WEST – Results – **Conclusions**

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- Use results to inform federal funding for water programs.
- Conduct analyses of additional water systems to determine what most affects results.
- Encourage water systems to more closely track material and energy use in systems.
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Method – Significance – WEST – Results – **Conclusions**

Thanks to…

- National Science Foundation Graduate Fellowship Program
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For more information

- http://www.ce.berkeley.edu/~horvath/west.html
- jrstokes@cal.berkeley.edu

Appendix B.2.4:

The Life-cycle Climate Change Contributions of Water Systems

J. Stokes (2007). “The Life cycle Climate Change Contributions of Water Systems” Peninsula AWWA Meeting, December 5.

The Life-cycle Climate Change Contributions of Water Systems

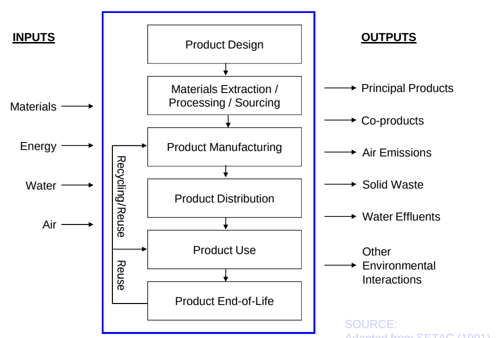
Jennifer Stokes, Ph.D.
Arpad Horvath, Associate Professor
University of California, Berkeley
Department of Civil and Environmental Engineering
Consortium on Green Design and Manufacturing
(cgdm.berkeley.edu)

December 5, 2007
Peninsula AWWA Meeting

Methodology

A Primer on
Life-cycle Assessment

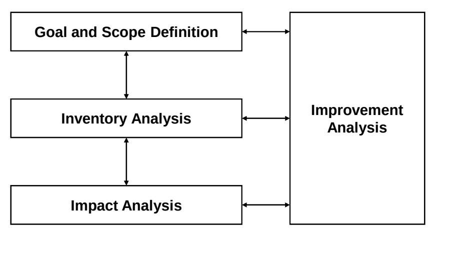
Life-cycle Assessment (LCA) Framework



SOURCE: Adapted from SETAC (1991)

Method – Significance – WEST – Results – Conclusions

LCA Methodology – ISO 14040



Source: Graedel (2003)

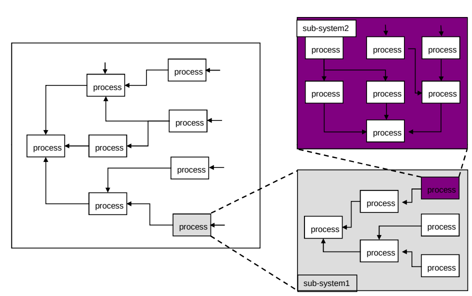
Method – Significance – WEST – Results – Conclusions

LCA Models

- Process-based LCA, developed by SETAC, EPA, and ISO, based on unit process models, process flow diagrams
  - Primary basis for ISO 14000 standards
  - Goal is to include all processes but can be limited by time or financial resources
- Economic input-output analysis-based LCA (EIO-LCA)
  - Developed by Carnegie Mellon University's Green Design Initiative
  - Boundary is by definition the entire economy, recognizing interrelationships among industrial sectors

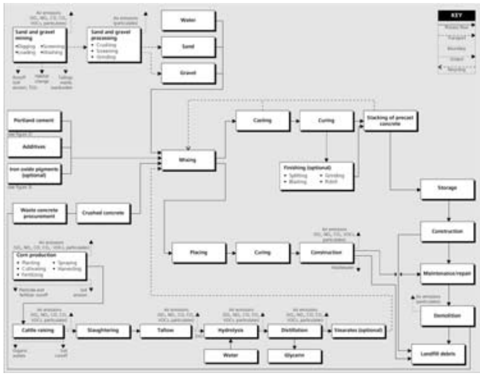
Method – Significance – WEST – Results – Conclusions

Structure of Process-based LCA



Method – Significance – WEST – Results – Conclusions

Process Flow of Cement Concrete



Source: AIA, "Environmental Resource Guide," John Wiley & Sons, 1997

Economic Input-Output Analysis-based LCA Model

Model Input

$1 M Demand for Motor Vehicles (F) →

Economic Input-Output Matrix (485 x 485 Sector)

Environmental Matrix (discharge or resource/ $ sector output)

→ Model Output

Environmental Effect Associated with the Specified Demand

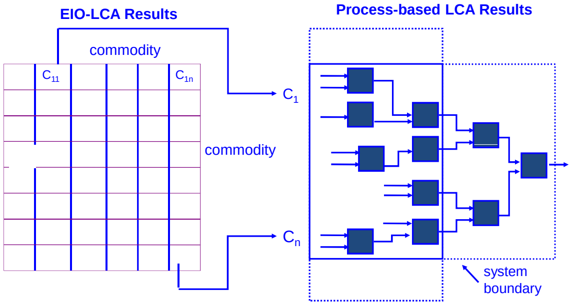
Example of Model Output

	Economic (1992$)	Energy TJ	Iron Ore kg	NOx kg
Total				
Motor Vehicles	x	e		
Steel				

$X = [I - D]^{-1} F$

$E = R X = R[I - D]^{-1} F$

Hybrid LCA



[Horvath 2003]

http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

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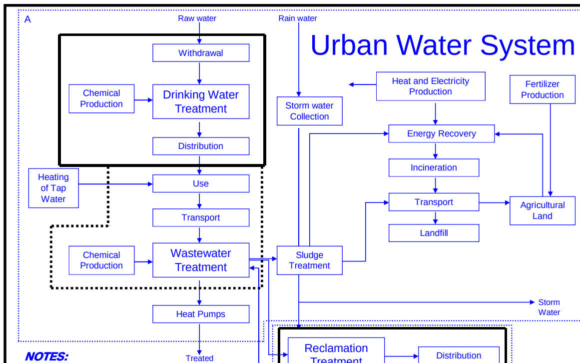
- Compare supply *alternatives* using California case studies

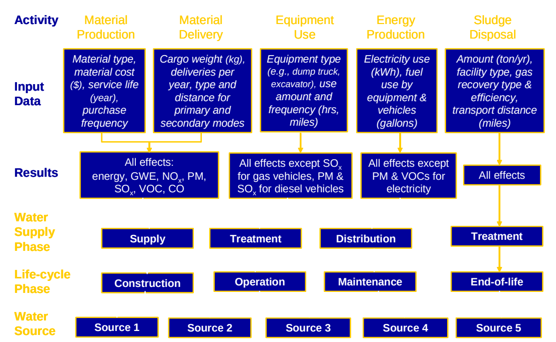
Method – Significance – **WEST** – Results – Conclusions



NOTES:
Bold outlines research boundaries. Dashed indicates current work.
Section A from [Lundin 2002].
Section B from [Stokes 2004]

Method – Significance – **WEST** – Results – Conclusions

WEST Structure



Examples: Surface water, groundwater, imported water, desalinated water, recycled water

Method – Significance – **WEST** – Results – Conclusions

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Method – Significance – WEST – **Results** – Conclusions

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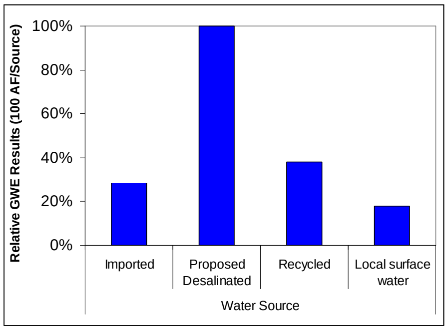
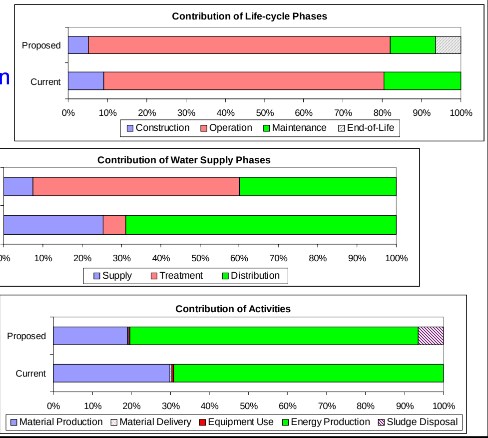
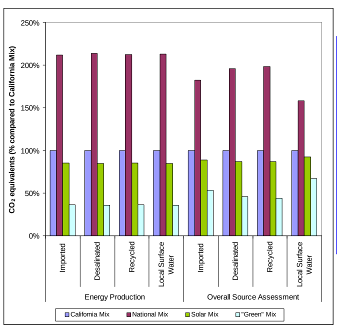


Method – Significance – WEST – **Results** – Conclusions

GWE Results Breakdown



Supplying Water with Alternative Energy



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Method – Significance – WEST – **Results** – Conclusions

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Method – Significance – WEST – **Results** – Conclusions

Conserving Water

- Compared conserving and supplying an equivalent volume of water.
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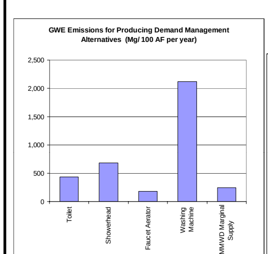
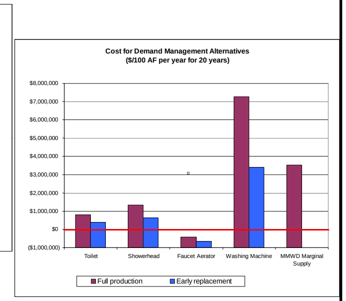
Method – Significance – WEST – **Results** – Conclusions

Water Conservation Results





Method – Significance – WEST – **Results** – Conclusions

Conclusions

Key Results

- Operation phase is key. The dominant water supply phase depends on the water source.
- Electricity generation produces most effects (>70%), followed by material production (<30%).
- We can't rely solely on desalination. Producing desalinated water for MWD (Southern California) would consume more than 13% of the state's current electricity consumption, assuming MMWD technology.
- Using solar power (PV) would not substantially lower GHG emissions below the California energy mix.
- Results are case-specific and are sensitive to electricity use and emission factors, water production, and material production emission factors (e.g., RO membranes, pipes).

Method – Significance – WEST – Results – **Conclusions**

Recommendations

- Incorporate LCA into long-term water supply planning process, such as Urban Water Management Plans.
- Conduct analyses of additional water systems to determine what most affects results.
- Encourage water systems to more closely track material and energy use in systems.
- Reassess desalination and alternative energy results as technology improves.
- Use results to inform federal funding for water programs.
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Method – Significance – WEST – Results – **Conclusions**

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For more information

- http://www.ce.berkeley.edu/~horvath/west.html
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Appendix B.2.5:
Energy Use and Greenhouse Gas Emissions of Wastewater Services: A Life-cycle View

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.

Energy Use and Greenhouse Gas Emissions of Water & Wastewater Services: A Life-cycle View

Jennifer Stokes, Ph.D.
Arpad Horvath, Associate Professor
University of California, Berkeley
Department of Civil and Environmental Engineering
Consortium on Green Design and Manufacturing
(cgdm.berkeley.edu)

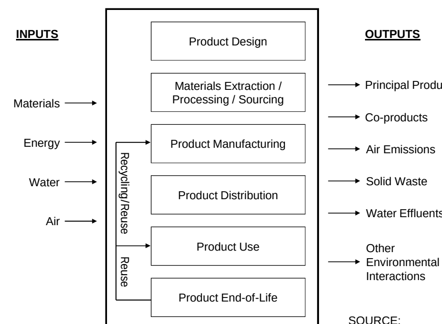
April 24, 2008
AWWA California-Nevada Conference

Introduction to Life-cycle Assessment

A Primer on the Method

http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

LCA Framework



SOURCE:
Adapted from SETAC (1991)

Why use LCA?

- To quantify the material and energy consumption of processes in the system
- To quantify the environmental emissions associated with system construction, operation, maintenance, and vehicle operation
- To consider the supply chain in a complete assessment
- To compare design alternatives
- To identify where improvements can be made in system design or operation
- To understand complete greenhouse gas emissions for better regulatory compliance

Global Warming Solutions Act (AB-32)

- Long-term goal: 80% below 1990 GHG emission levels by 2050
- Mandatory reporting process/combustion emissions and energy purchases coming soon
- Focus on eight strategies to achieve half the goal, potentially includes some POTWs
- Creates environment where assessing GHG emissions in planning decisions is encouraged statewide

The Water-Energy Sustainability Tool (WEST)

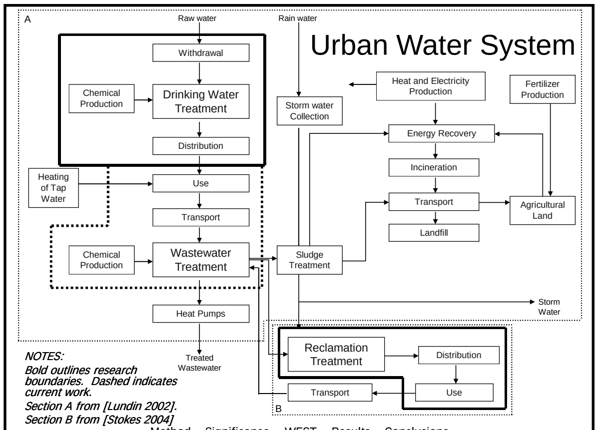
A Research Overview

Research Objectives

- Create a *model* to identify and inventory inputs to and outputs from water systems over the life-cycle
- Quantify the *environmental effects* of these systems (energy use, greenhouse gas emissions, air emissions)
- Develop a *tool* to assist interested parties in assessing the environmental effects of their water supply decisions using current and potential energy mixes
- Compare supply *alternatives* with California case studies

Method – **WEST** – Results – WWEST – Conclusions

Urban Water System



NOTES:
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Section A from [Lundin 2002].
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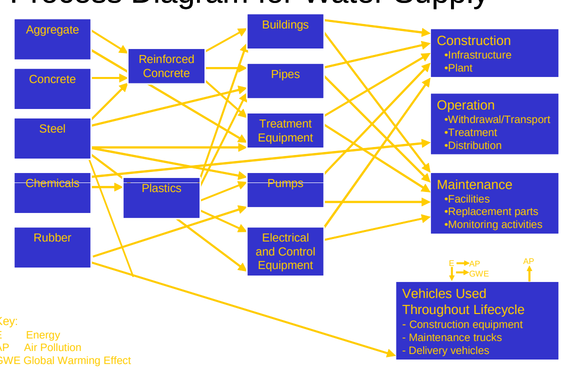
Method – Significance – WEST – Results – Conclusions

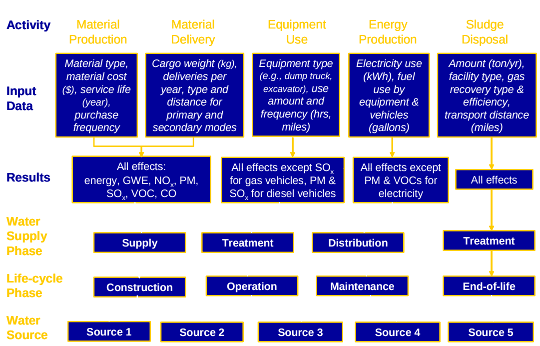
Process Diagram for Water Supply



Key:
E Energy
AP Air Pollution
GWE Global Warming Effect

Method – **WEST** – Results – WWEST – Conclusions

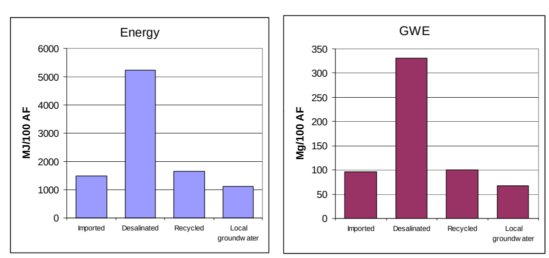
WEST Structure



Examples: Surface water, groundwater, imported water, desalinated water, recycled water

Method – Significance – **WEST** – Results – Conclusions

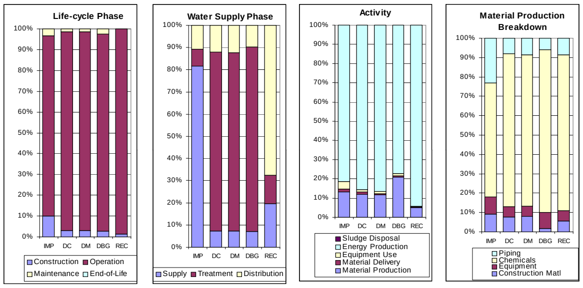
Energy Consumption and Global Warming Results



Note: Results shown are for illustrative purposes; DO NOT CITE.

Method – WEST – **Results** – WWEST – Conclusions

Relative System Energy Results

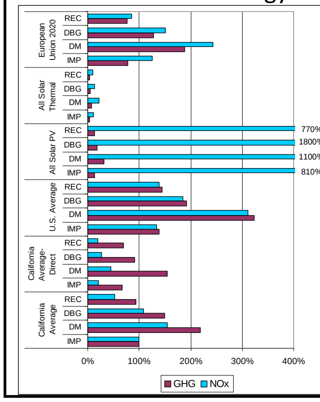


WATER SOURCES: IMP- Imported (CRA/SWP) DC- Desal and conventional pre-treatment DM- Desal and membrane pre-treatment DBG- Desal, brackish groundwater REC- Recycled

Note: Results shown are for illustrative purposes; DO NOT CITE.

Method – WEST – **Results** – WWEST – Conclusions

Alternative Energy Source Comparison



	California State Mix	U.S. Average Mix	European Union 2020 Projected Mix
Coal	1%	53%	1%
Oil	1%	3%	1%
Natl Gas	50%	15%	36%
Nuclear	17%	19%	12%
Other fossil fuels	1%	1%	1%
Hydro	19%	7%	14%
Biomass	3%	1%	8%
Wind	2%	0%	14%
Solar thermal	--		0%
Geo-thermal	6%	0%	0%
Small hydro	--		10%
Solar PV	0%	0%	1%
Total	100%	100%	100%

Note: Results shown are for illustrative purposes; DO NOT CITE.

Sensitivity and Uncertainty

- Using a Monte Carlo assessment, we identified the components of the system that most affect the final results.
- Some sensitive parameters from prior studies included:
  – Consumer water demand
  – Proportion of water from each source
  – Electricity consumption and emission factors
  – Costs and production emission factors for metal and concrete piping and appurterences
  – Chemical production emission factors
  – Control equipment service life
  – Sludge disposal volume and emission factors

Method – WEST – **Results** – WWEST – Conclusions

The Wastewater-Energy Sustainability Tool (WWEST)

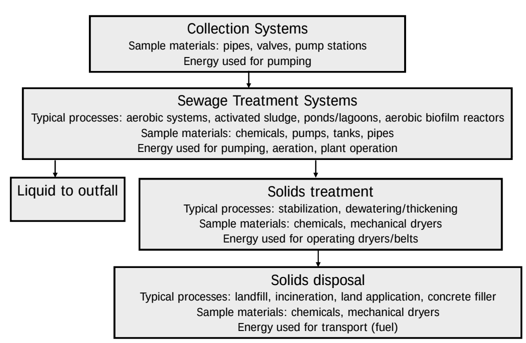
A Research Overview

Wastewater Analysis Includes:

- Construction
  – Producing construction materials (concrete, pipe, steel)
  – Operating delivery vehicles and construction equipment
- Operation
  – Producing chemicals and electricity
  – Operating generators
  – Process emissions of greenhouse gases, especially methane
- Maintenance
  – Producing maintenance materials (replacement pumps, pipes, membranes)
  – Operating maintenance vehicles
- Results include energy consumption, greenhouse gas emissions, criteria air pollutants

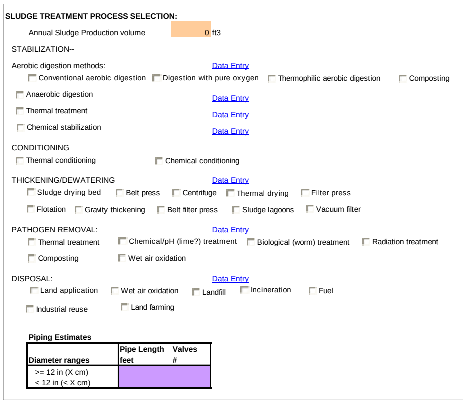
Method – WEST – Results – **WWEST** – Conclusions

Typical Wastewater System Model



Method – WEST – Results – **WWEST** – Conclusions

WWEST Sample Data Entry


SLUDGE TREATMENT PROCESS SELECTION:

Annual Sludge Production volume 0 ft3

STABILIZATION--

Aerobic digestion methods: Data Entry

Conventional aerobic digestion; Digestion with pure oxygen; Thermophilic aerobic digestion; Composting

Anaerobic digestion — Data Entry

Thermal treatment — Data Entry

Chemical stabilization — Data Entry

CONDITIONING

Thermal conditioning; Chemical conditioning

THICKENING/DEWATERING — Data Entry

Sludge drying bed; Belt press; Centrifuge; Thermal drying; Filter press

Flotation; Gravity thickening; Belt filter press; Sludge lagoons; Vacuum filter

PATHOGEN REMOVAL: Data Entry

Thermal treatment; Chemical/pH (lime?) treatment; Biological (worm) treatment; Radiation treatment

Composting; Wet air oxidation

DISPOSAL: Data Entry

Land application; Wet air oxidation; Landfill; Incineration; Fuel

Industrial reuse; Land farming

Piping Estimates

Diameter ranges	Pipe Length feet	Valves #
>= 12 in (X cm)		
< 12 in (< X cm)		

Method – WEST – Results – **WWEST** – Conclusions

Conclusions

Conclusions

- LCA and WEST have been successfully used to better understand the energy and environmental effects of certain water systems.
- Results are largely case-specific and are sensitive to electricity use and emission factors, volume of water produced, and emission factors for material production (e.g., RO membranes, piping).
- Additional case study analyses will provide more insight and generalized results.
- LCA will be used to also analyze wastewater systems to provide information about collection system design, treatment process decisions, and sludge processing and disposal alternatives.

Method – Significance – WEST – Results – **Conclusions**

About the future…

- Work will continue through Dec 2009.
- We are seeking partner case study utilities to gain more data (both water and wastewater systems).
  - Interested or want more info? Contact: jrstokes@cal.berkeley.edu
- We are planning a series of workshops to introduce WEST to the industry; anticipated in 2009.

Method – Significance – WEST – Results – **Conclusions**

Thanks to…

- National Science Foundation Graduate Fellowship Program
- University of California Toxic Substances Research and Teaching Fellowship
- California Energy Commission Public Interest Energy Research Grant –Environmental Area [Contract Number 500-02-004]

For more information

- http://www.ce.berkeley.edu/~horvath/west.html
- jrstokes@cal.berkeley.edu

Appendix B.2.6:
A Cradle-to-Cradle Assessment of Energy and Climate Change Impacts of Recycled Water

J. Stokes (2009). “A Cradle-to-Cradle Assessment of Energy and Climate Change Impacts of Recycled Water”, WateReuse California Section Conference, San Francisco, California, March 23.

A Cradle-to-Cradle Assessment of Energy and Climate Change Impacts of Recycled Water

Jennifer Stokes, Ph.D.
Arpad Horvath, Associate Professor
University of California, Berkeley
Department of Civil and Environmental Engineering
Consortium on Green Design and Manufacturing
(cgdm.berkeley.edu)

March 23, 2009
WateReuse Conference

Water and Energy

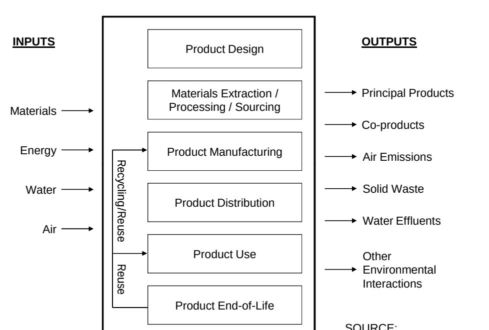
- 2-3% of global energy is used for water and wastewater services; will grow by 33% in next 20 years [ASE 2002]
- Water-related services in California use approximately 19% of electricity, 30% of natural gas, and almost 100 billion gals of fuel annually [CEC 2005]. The SWP is the largest electricity consumer in the state.
- Eight western states have "substantial" or "high" probability of water shortages by 2025 [USDOI 2003]
- No comprehensive study of the environmental effects of U.S. urban water systems has been conducted. Wastewater studies have been focused on other countries.

Introduction to Life-cycle Assessment

A Primer on the Method

http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

LCA Framework



SOURCE:
Adapted from SETAC (1991)

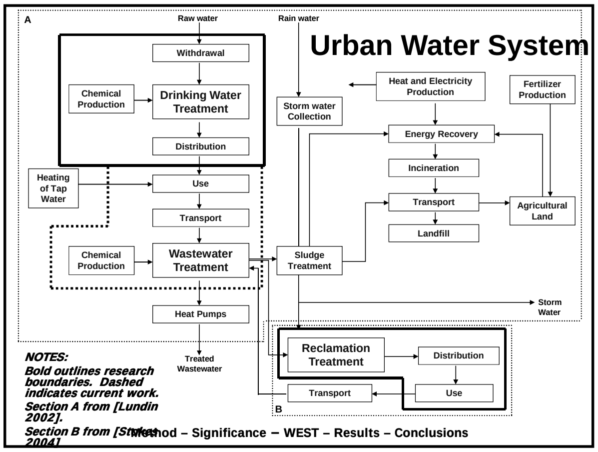
Why use LCA?

- To quantify the material and energy consumption of processes in the system
- To quantify the environmental emissions associated with system construction, operation, maintenance, and vehicle operation
- To consider the supply chain in a complete assessment
- To compare design alternatives
- To identify where improvements can be made in system design or operation
- To understand complete greenhouse gas emissions for better regulatory compliance

Water-Energy Sustainability Tool

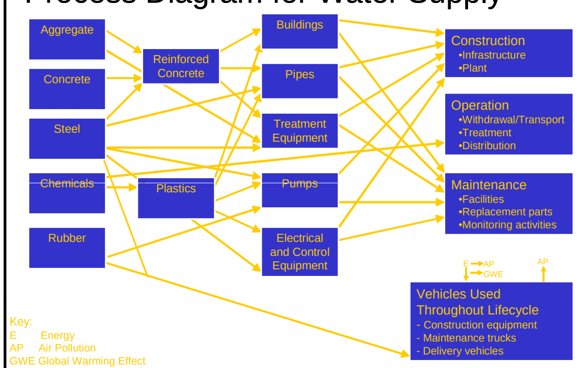
A Research Overview

Urban Water System



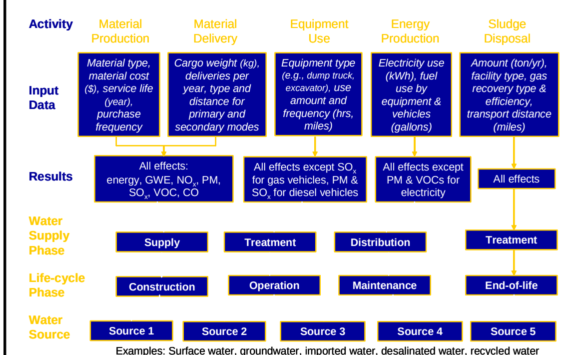
Method – Significance – WEST – Results – Conclusions

Process Diagram for Water Supply



Significance – Method – **WEST** – Results – Conclusions

WEST Structure



Significance – Method – **WEST** – Results – Conclusions

Life-cycle Assessment Results

California Case Study

- Hypothetical system in Southern California currently using imported water (CRA/SWP), considering new sources:
  - Seawater desalination (conventional pretreatment)
  - Seawater desalination (membrane pretreatment)
  - Brackish water desalination
  - Recycled water
- Compared water sources including typical N. California imported water, S. California imported water, desalinated seawater, brackish groundwater, and small and large recycled water system

Significance – Method – WEST – **Results** – Conclusions

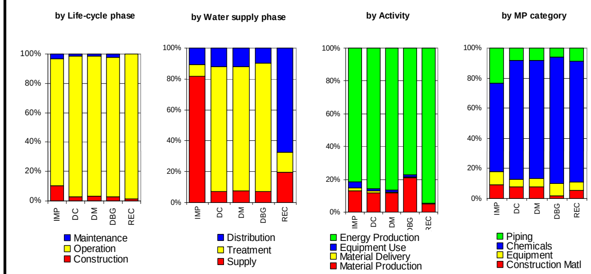
Energy and GHG Results

Water Source	For annual per capita consumption[1] Energy GJ	GHG kg CO2eq.	For California's statewide supply[2] Energy TJ	% of Ca. electricity	GHG Tg CO2eq.	% of Ca. emissions
IMP	5.8	360	210,000	22%	13	2.6%
DC	14	800	500,000	52%	29	6.0%
DM	13	780	490,000	51%	29	5.8%
DBG	8.9	530	320,000	34%	19	3.9%
REC	5.5	330	200,000	21%	12	2.5%

For Southern Cal hypothetical system
WATER SOURCES: IMP- Imported (CRA/SWP) DC- Desal, conventional pre-treatment
DM- Desal, membrane pre-treatment DBG- Desal, brackish groundwater REC- Recycled
Source: Stokes and Horvath, ES&T, 2009

Significance – Method – WEST – **Results** – Conclusions

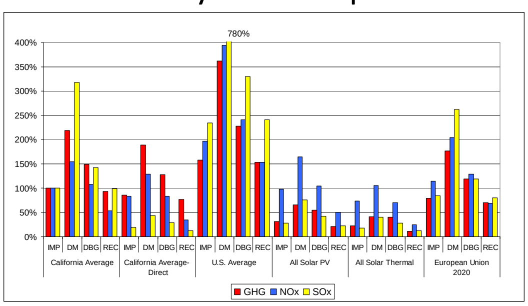
Relative System Energy Results



For Southern Cal hypothetical system
WATER SOURCES: IMP- Imported (CRA/SWP) DC- Desal, conventional pre-treatment
DM- Desal, membrane pre-treatment DBG- Desal, brackish groundwater REC- Recycled
Source: Stokes and Horvath, ES&T, 2009

Significance – Method – WEST – **Results** – Conclusions

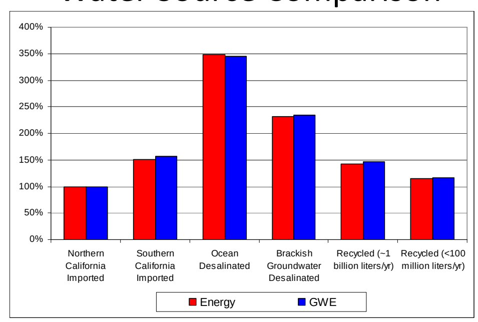
Electricity Mix Comparison



For Southern Cal hypothetical system
WATER SOURCES: IMP- Imported (CRA/SWP) DC- Desal and conventional pre-treatment
DM- Desal and membrane pre-treatment DBG- Desal, brackish groundwater REC- Recycled
Source: Stokes and Horvath, ES&T, 2009

Significance – Method – WEST – **Results** – Conclusions

Water Source Comparison



Average per capita water use in California is 326,000 L/yr
Source: Stokes and Horvath, ES&T, 2009

Significance – Method – WEST – **Results** – Conclusions

Sensitivity and Uncertainty

- Using a Monte Carlo assessment, we identified the components of the system that most affect the final results.
- Some sensitive parameters from prior studies included:
  - Consumer water demand
  - Proportion of water from each source
  - Electricity consumption and emission factors
  - Costs and production emission factors for metal and concrete piping and appurterences
  - Chemical production emission factors
  - Control equipment service life
  - Sludge disposal volume and emission factors

Significance – Method – WEST – **Results** – Conclusions

Conclusions

Conclusions

- LCA and WEST have been successfully used to better understand the energy and environmental effects of certain water systems.
- Results are largely case-specific and are sensitive to electricity use and emission factors, volume of water produced, and emission factors for material production (e.g., RO membranes, piping).
- Additional case study analyses will provide more insight and generalized results.
- LCA will be used to also analyze wastewater systems to provide information about collection system design, treatment process decisions, and sludge processing and disposal alternatives.

Significance – Method – WEST – **Results** – Conclusions

About the future…

- Work will continue through mid-2010.
- We are seeking partner case study utilities to gain more data (both water and wastewater systems).
  - Interested or want more info? Contact: jrstokes@cal.berkeley.edu
- We are planning a series of workshops to introduce WEST to the industry; anticipated in 2009.

Significance – Method – WEST – **Results** – Conclusions

Thanks to…

California Energy Commission Public Interest Energy Research Grant –Environmental Area

For more information

- http://www.ce.berkeley.edu/~horvath/west.html
- jrstokes@cal.berkeley.edu
- Stokes & Horvath, Energy & Air Emission Effects of Water Supply, *Environmental Science & Technology*, available online 3/20/09
- Stokes & Horvath, Life-cycle Energy Assessment of Alternative Water Supply Systems, *Intl J of LCA*, 11(5), 2006

Appendix C: Task 2

Appendix C.1: Detailed Changes to WEST C-2

Appendix C.2: Detailed Description of Desalination Case Study C-6

Appendix C.1:
Detailed Changes to WEST

Data Entry Modifications

The following describes changes made to the Data Entry pages of WEST:

- Created "Energy Mix" data entry worksheet. Previously the energy mix selection only involved indicating the state where the water system was located on the "Project Information" worksheet. The emission factors for the state's average electricity mix were then used in the calculations. The new worksheet allows the user to select the energy mix scenario, whether consumption or generation mix should be used, whether default emission factors or user-defined emission factors should be used, and whether direct or life-cycle emissions should be used. In addition, the user can now define an Assumed Distribution loss to account for energy which must be generated at the plant to meet the required demand but which is lost in distribution. In the prior iteration of WEST, these losses were assumed to be zero. Each of these selections is discussed further below.
- The following drop-down menus were added to the Energy Mix worksheet:
  - The Scenario selection allows the user to select whether the emission factors used should be taken from the State Average Mix, the Marginal Generation Source, or a Custom Generation Mix. The emission factors for energy use and carbon monoxide (CO) are based on the same sources have not changed from the original version of WEST[1].

    However, if:

    * the State Average Mix is selected, WEST functions as it did prior to these revisions. The default emission factors were calculated using data from the Environmental Protection Agency's (EPA) Emissions and Generation Resource Integrated Database 2002 (E-GRID) [EPA 2006], as described in the Emission Factor Calculation section below. Data from the Year 2000 Location file, Plant Data worksheet was manipulated to obtain the emission factors. The values provided in the Default Emission Factors table are selected based on the state where the water system is located as defined on the project information worksheet. The default values may be edited in the lower table if User-defined Values is also selected.

    * the Marginal Generation Source is selected, then emissions associated with coal generation are used. A drop-down menu was created which allows the user to define which source would be used for marginal generation. However, since this was out-of-scope, the calculations were not edited to allow for non-coal

[1] The energy use emission factors is a unit conversion, 3.6 megajoules per kilowatt-hour (MJ/kWH). The CO emission factor is calculated based on data from [Monterey 2003].

sources. The default values may be edited in the lower table if User-defined Values is also selected.

* the Custom Generation Mix is selected, the user can define the percentage of their electricity which comes from each of the nine potential sources (coal, gas, oil, nuclear, other fossil fuels, biomass, wind, solar , geothermal). If the sum of the sources is less than one, the remainder of the electricity is assumed to have emissions of the state average mix. If the sum of the sources is greater than one, it is assumed the water system will sell energy back to the grid and it will offset production of the state average mix. Both the percentage of electricity from each source and the emission factor associated with the source can be edited in the lower table if User-defined Values is also selected.

- The Generation/Consumption selection will allow the user to determine whether they want their energy mix to reflect the electricity generated within their state or the electricity consumed within their state. E-GRID provides data for electricity generation. However, because of interstate trading, these values may not fully reflect the emissions associated with electricity consumed in the state. The emissions associated with electricity consumed in each state for coal, oil, gas, hydro, and other were estimated by [Marriott 2005]. Emission for other sources must be interpolated. The Consumption data is included in the tool on the "Electricity Data 00". Interpolated values were not finalized. Because this task is out-of-scope, it was not completed and Consumption values are not available at this time.

- The Marginal Source menu will allow the user to choice which electricity source is used for marginal electricity production. The default values are for coal generation. The marginal source selection is out-of-scope and was not completed.

- The Default or User-defined menu allows the user to select whether they want to use the emission factors available in WEST as shown in the top table or edit the information in the bottom table with user-defined emission factors.

- The Direct or Life-cycle emission factors menu allows the user to define whether they want to use the direct emission factors (primarily from E-GRID) or life-cycle emission factors (compiled from literature). The life-cycle emission factors will be added as part of Task 5 in 2007.

• Added two tables onto the "Energy Mix" data entry worksheet. The upper table is for the default emission factors. The lower table is for user-defined emission factors. In the upper default values table, the user may edit the distribution loss assumptions for any of the selected sources and, when custom generation mix is selected, may edit the percentage of the mix from each source. Cells which are shaded with a dot pattern are not relevant for the calculations based on the options selected in the drop-down menus and should not edited. In the lower table, any cells which are not shaded with a dot pattern may be edited by the user. The unshaded values in these tables are used in the Energy Production calculations.

Revised Emission Factor Calculations

As part of this task the direct emission factors for CO_2, NO_x, and SO_x were updated to be source-specific. These emission factors will allow the user to specify a customized energy mix and calculate associated emissions. The Energy Use factors and CO emission factors were not changes. VOC and PM emission factors were not included in the original WEST tool and have not been added at this time.

To obtain the required emission factors, the E-GRID Year 2000 Location data sheets were used. The Plant worksheet was copied. This sheet contains information on every plant in every state which reports emissions to the EPA and includes non-traditional sources such as electricity produced from off-gas at landfills and small hydropower generation. Using guidance available in E-GRID documentation (available online), each plant was classified into one of ten electricity sources (coal, oil, natural gas, nuclear, hydropower, other fossil fuels, biomass, wind, solar, geothermal, and municipal solid waste). Municipal solid waste does not appear as a category in the final version of E-GRID; the data associated with generation from municipal solid waste sources were allocated to biomass (70%) and other fossil fuels (30%) as specified in the E-GRID documentation.

The national average emission factors (EF; g/kWh) were calculated for each source *i* as follows:

$$EF_i = \frac{Emissions_i * 907184.74}{Generation_i * 1000}$$

Similarly, for each source *i*, an average emission factor for each state *j* was calculated using the following equation:

$$EF_{ij} = \frac{Emissions_{ij} * 907184.74}{Generation_{ij} * 1000}$$

E-GRID reported emissions in pounds; the factor 907184.74 converts pounds to grams. Generation was reported in megawatt-hours and was converted to kWh by multiplying by 1000.

The calculated emission factors were compiled for every state. If a particular source was used in the state, the state-specific emission factor was used. If generation for a source was zero, the national average emission factor was used. All nation and state average emission factors are provided on the EGRID EFs worksheet. The emission factors for the state selected on the Entry-Project Info worksheet are shown in the upper table on the Entry-Energy Mix worksheet.

Energy Production Calculation Modifications

The energy production calculations were edited to 1) account for the increased complexity of emission factors and 2) incorporate the distribution losses assigned by the user. The revised equations for energy use (a) and emissions (b) are provided below.

a)

$$Energy = \frac{UseFactor * TotalkWh * \sum_{sources}[(1 + DistributionLoss) * SourceContribution]}{FUA}$$

b)

$$Emissions = \frac{EmissionFactor_i * TotalkWh * \sum_{sources}[(1 + DistributionLoss) * SourceContribution]}{1{,}000{,}000 * FUA}$$

Where the Emission or Use Factor for each pollutant i is displayed on the Entry-Energy Mix worksheet in the upper table if default values are selected and in the lower table if user-defined values are selected. The factors are specific to the state specified in the 'System Information' table on the Entry-Project Info worksheet. Total kWh is specified on the Entry-Energy Use worksheet, and the Functional Unit Adjustment (FUA) is calculated as described in the original WEST documentation (see Attachment 3). The factor of one million converts grams to Mg. The Distribution Loss and Source Contribution are defined on the Entry-Energy Mix worksheet.

Appendix C.2:
Detailed Description of Desalination Case Study

Excerpt from: Stokes, J. and A. Horvath (2004). "Life-cycle Assessment of Alternative Water Supply Systems in California." *Proceedings of the 2004 A&WMA Annual Meeting*, Indianapolis, IN. June 22-25, 2004.

Supply

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

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

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

Treatment

Water is desalinated through an RO process. Facilities at the desalination plant include an RO equipment building, an auxiliary building containing an office, laboratory, warehouse, and chemical storage, an outdoor chemical storage area, and a paved driveway and parking lot.

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

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

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

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

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

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

Table 1: Chemical Use and Storage

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

Distribution

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

Appendix D:
Task 3 Detailed Changes to WEST

Data Entry Modifications

- Edited "Project Info" data entry worksheet to allow the user to enter customized names for the water sources they want to consider into the Source Information table. Up to 5 different sources are allowed. Previously WEST only allowed three pre-defined sources (imported, desalinated, and recycled water). These 5 sources are then used to populate the relevant portions of the Water Sources table and the Facility table and define the drop-down lists used for water source selection.
- Rearranged the "Project Info" data entry page to show the Model and Source Information tables on the left. Because the sources are used to populated headings in the System Information table, this configuration is more intuitive.
- Removing the "% Water System" term from the calculations. Originally, this term was intended to account for imported supply systems that provide water to multiple systems (i.e., where only half the water is actually used by the considered utility). The original logic was that if in the average functional unit of water produced in the supply facility only 50% was being used by the considered utility then only 50% of the effects should be allocated to the considered utility. In fact, the calculation should include the overall effects of producing a functional unit of water in the supply facility, regardless of where it ends up. If the entire functional unit of imported supply water in the utility comes through the supply facility, then the entire effects of the producing an average functional unit of water in the facility should be included.

  As an example, consider Utility X which purchases imported water from Utility Y. Utility Y has a pipeline that carries 10,000 AFA of water, half of which it sells to Utility X and half it uses itself. All of Utility X's imported water comes through that pipeline. If we are interested in determining the effects of producing 100 AF of imported water in Utility X's system, we must calculate the average effect of producing 100 AF of water in the pipeline of Utility Y. The fact that 50% of the water goes elsewhere is irrelevant. The "% to Water System" term previously caused, in this example, the final results for this component of imported supply to be 50% too low.

  For this analysis, the authors set all "% water to system" terms to remove the effect. We also removed the term from the "Entry-Project Info" page and revised all calculations and explanatory pages to remove the term from all equations.
- Correcting an error in prior WEST tool with the "Entry-Project Info" worksheet documentation. In the Facilities table, the Water Sources % explanation was changed so in the future, the percentage entered is for the percent of water from that source processed in the facility, rather than the percentage of water in the facility that comes from the source. However, by similar logic as above, this term caused construction and

maintenance effects to be artificially lower. The change particularly affects results for potable distribution systems, often shared between sources.

Results Modifications

All tables and graphs on the Results worksheets were edited to incorporate the five user-defined water sources rather than the original three pre-defined sources. In addition, the results are now reported in two different ways:

- Source Assessment: Results compare considered sources by providing results for producing a functional unit of water from each of the defined sources
- System Assessment: Results indicate the overall environmental burden created by the water system by allocating the contribution of each source proportionally by its contribution to overall water production

Calculations Modifications

Allocation factors for each of the activities have been restructured and simplified. Previously, the table had a column for each of the combination of life-cycle phase, water supply phase, and water source, 27 columns in all.

The addition of two water sources (18 columns) would have made the worksheets unwieldy. Instead, each worksheet has a column for each life-cycle phase (either 0 or 1 for construction and operation, can be fractional for maintenance), a column for each water supply phase (either 0 or 1), and a column for each water source (can be fractional depending on data entered in the facility table).

The values in these columns are multiplied together to allocate the results properly. The results from the revised WEST were compared to previous results to ensure the restructured system provides the correct results. By simplifying the allocation factors, the size of the base WEST file was reduced from approximately 7 MB to 5 MB.

Appendix E: Task 4

Appendix E.1: WESTLite Tool **separate file**

Appendix E.2: WestLite Help Pages

Appendix E.3: Pipe Analysis Assumptions

Appendix E.4: Tank Analysis Assumptions

Appendix E.1:
WESTLite Tool

This appendix is available as a separate volume, Appendix E.1_WESTLite.xls

Appendix E.2:
WestLite Help Pages

Appendix E.2:
WEST Lite Help Pages

Purpose: The purpose of this tool is to allow users to assess simple modules of a water system without using the full functionality of WEST. It is intended to be used for "back-of-the-envelope" assessment.

Contents:

- **Input Key**
- **Pipe Documentation**
  - Pipe Summary
  - Pipe Inputs
  - Pipe Calculations
- **Tank Documentation**
  - Tank Summary
  - Tank Inputs
  - Tank Calculations

Input Key

(yellow box)	User may enter custom data in yellow boxes
(tan box)	User may select from drop-down menus in tan boxes.
(hatched box)	Boxes filled with hatching are not relevant given current user selections.
	NA = Not applicable

PIPE ANALYSIS DOCUMENTATION

Pipe Summary: This module allows the user to compare production of pipe made of four materials: polyvinyl chloride (PVC), concrete, ductile iron (DI), and steel. Up to 5 different diameters can be included in the analysis. Besides PVC, the pipe may be coated and/or mortar-lined, depending on user selections. Gaskets are included in the analysis as well.

PIPE USER INPUT DOCUMENTATION

Pipe Inputs: User may enter an length of pipe to be analyzed (feet; default: 100) and an analysis period (years; default: 75). The user may select up to five different pipe diameters to include in the analysis (inches; defaults: 6, 12, 24, 36, 60), The user may then select coating and lining options from the drop-down menus. Finally, the user should edit the service lives and pipe segment lengths for the different materials, as needed.

Length of pipe considered	The user should enter the length of pipe they would like to consider in feet. The default value is 100.
Analysis Period	The user should enter the desired analysis period in years. The recommended analysis period is equivalent to the maximum service life of the pipe materials. The default value is 75.
Pipe Diameter	The user should select up to 5 pipe diameters in inches for analysis from the drop-down menu. The pipe diameter alternatives include: 2, 6, 12, 18, 24, 30, 36, 48, 60, and 72.

Pipe Improvement Options Table

Purpose: This table allows the user to select the applicable pipe improvements (lining and coating) for each of the pipe materials to use in the analysis.

Mortar lining	The user should select either 'Yes' or 'No' from the drop-down menu. Lining is not an alternative for the PVC pipe.
Coating	The user should select either 'Yes' or 'No' from the drop-down menu. Coating is not an alternative for the PVC or concrete pipe.
Coating Selection	The user should select the appropriate coating for DI and steel pipe, if applicable. The cell remains hatched if coating is not chosen in the Coating column. For DI pipe, the alternatives are ashpalt and polyethylene tube. For steel, the alternatives are epoxy, tape, and polyethylene tube.

Pipe Details Table

Service Life	The user should enter the expected service life in years for each of the materials listed.
Pipe Segment Length	The user should enter the length of each segment of pipe (i.e., the distance between connections) in feet for each pipe material. This value is used to calculate the effects of connections (e.g., gasket production).

PIPE CALCULATIONS DOCUMENTATION

Production Emissions

Total emissions (or energy use) are calculated as follows for each chemical i:

$$Emissions_i = PipeEmissions_i + GasketEmissions_i + MortarEmissions_i + CoatingEmissions_i$$

Emissions and energy use for pipe production are calculated for each chemical i as follows:

$$Emissions = \frac{EIOLCAEF * PipeCost * PipeL * AnalysisPeriod}{PipeLife}$$

Where the "EIOLCAEF" (EIOLCA Emission Factor) [grams/1997$ for chemicals and MJ/1997$ for energy use] is defined on the *EIOLCA EFs* worksheet, "pipe cost" [1997$/length {ft}] is defined on the *Cost* worksheet (based on estimates from Mean's guide), and "pipe l" (pipelength) [ft], "analysis period" [yrs], and "pipe life" [yrs] are defined by the user on the *Pipe User Input* worksheet.

Emissions and energy use for gasket production are calculated for each chemical i as follows:

$$Emissions = \frac{EIOLCAEF * GasketCost * PipeL * AnalysisPeriod}{PipeSegmentL * GasketLife}$$

Where the "EIOLCA EF", "pipe l", analysis period", and "gasket life" are described above, "gasket cost" [1997$] is defined on the *Cost* worksheet (estimated from Mean's guide), and "pipe segment l" (pipe segment length) is defined by the user on the *Pipe User Input* worksheet.

Emissions and energy use for mortar production are calculated for each chemical i as follows:

$$Emissions = \frac{EIOLCAEF * PipeD * \pi * MortarH * PipeL * MortarCost * AnalysisPeriod}{3888 * MortarLife}$$

Where the "EIOLCAEF", "pipe l", and "analysis period" are described above, "mortar h" (height or thickness) [in] is defined with pipe costs on the Cost worksheet, "mortar cost" is defined on the *Cost* worksheet [$/cubic yard] (estimated from Mean's guide in 1997$), and "pipe d" (diameter) [in] and "mortarlife" are defined by the user on the *Pipe User Input* worksheet. The factor 3888 converts units to cubic yards.

Emissions and energy use for coating production are calculated for each chemical i as follows:

$$Emissions = \frac{EIOLCAEF * CoatingCost * PipeL * AnalysisPeriod}{CoatingLife}$$

Where the "EIOLCAEF", "pipe l", and "analysis period" are described above, "coating cost" is defined on the *Cost* worksheet [$/foot] (estimated from Mean's guide in 1997$), and "coating life" are defined by the user on the *Pipe User Input* worksheet.

TANK ANALYSIS DOCUMENTATION

Tank Summary: This module allows the user to compare production of four types of tanks, including concrete, steel, elevated steel, and wood. The calculation includes construction of tank materials, tank foundation, and additional pipe and electricity needs. These "additional needs" should be estimated to include extra material or energy required because of the location of the tank. For example, if a below-ground tank is being considered and water must be pumped from the tank to the customer, the additional electricity for that phase of pumping should be included. If the pipe will be placed at a higher elevation some distance from the remainder of the water system, the pipe needed to tie in the tank should be included.

Tank Inputs: User may enter the analysis period (default: 75 years), and foundation life (default: 75 years). User may select the tank capacity from a drop-down menu of the following choices: 0.75, 1, 2, 4, 5, 6, 8, and 10 million gallons (MG) (default: 1 MG). In addition, for each of the four types of materials (concrete, steel, elevated steel, and wood), the user must define the tank height (feet) and foundation thickness (feet). Other dimensions of the tank and foundation are calculated based on these input values and assumptions listed on the *Assumptions* worksheet.

TANK USER INPUT DOCUMENTATION

Analysis Period	The user should enter the desired analysis period in years. The default value is 75.
Tank Capacity	The user should select the desired tank capacity for analysis from the drop-down menu (in million gallons). The choices available are: 0.005, 0.1, 0.25, 0.5, 0.75, 1, 2, 4, 5, 6, 8, and 10. Steel and wood tanks are not available in sizes larger than 1 MG.
Foundation Life	The user should enter the service life for foundations in years. The default value is 75.

Tank Details Table

Service Life	The user should enter the service life in years for each tank type. The default value for concrete and steel tanks is 75 years and for wood tanks is 40 years.
Tank Height	The user should enter the tank height in feet for each tank height. This value is used to calculate the dimensions of the tank. This value is not need for the elevated steel tank.
Foundation Thickness	The user should enter the thickness of the foundation in feet.

Tank Configuration?	The user should select the hydraulic position of the tank in the water system. The choices are: above the hydraulic grade line, at the grade line, and below the grade line. Generally, elevated tanks or those places at high elevations, perhaps far from the existing distribution system, are at the hydraulic grade line and ground-level tanks are below the grade line. Tanks placed at the grade line may require additional piping ot connect the distribution system. Tanks placed below the hydraulic grade line require pumping to return the water to the correct pressure.
Electricity Mix	The user should select the state where the system is located; this defined the electricity mix that will be used in the calculations.
Annual Electricity Use	The user should enter the additional amount of electricity (in kilowatt-hours) needed because of the placement of the tank relative to system hydraulics. It is generally only needed for tanks placed above or below the hydraulic grade line.
Additional Pipe Required	The user should energy the additional pipe required (in feet) because of placement of the tank relative to the rest of the distribution system. The pipe is assumed to be PVC pipe with an 18-inch diameter. This is generally needed for tanks places at the hydraulic grade line.

TANK CALCULATIONS DOCUMENTATION

Production Emissions

Total emissions (or energy use) are calculated as follows for each chemical i:

$$Emissions_i = TankEmissions_i + FoundationEmissions_i + EnergyandPipingEmissions_i$$

Emissions and energy use for tank production (not including foundations) are calculated for each chemical i as follows:

$$Emissions = \frac{EIOLCAEF*TankCost*AnalysisPeriod}{TankLife}$$

Where the "EIOLCAEF" (EIOLCA Emission Factor) [grams/1997$ for chemicals and MJ/1997$ for energy use] is defined on the *EIOLCA EFs* worksheet, "tank cost" [1997$/length {ft}] is defined on and can be edited on the *Cost* worksheet (based on estimates from Mean's guide), and "analysis period" [yrs], and "tank life" [yrs] are defined by the user on the Tank *User Input* worksheet.

Emissions and energy use for foundation production are calculated for each chemical i as follows:

For concrete, steel, and wood tanks:

$$Emissions = \frac{EIOLCAEF*TankHt*FdtnDepth*RCCost*AnalysisPd*1.44*0.005}{FdtnLife}$$

Where the "EIOLCAEF", "analysis period (pd)", and "foundation (fdtn) life" are described above, "foundation (fdtn) depth" is defined on the *Tank User Input* worksheet, and "reinforced concrete (RC) cost" [1997$] is defined on the *Cost* worksheet (estimated from Mean's guide data for ready-mix concrete and reinforcing steel bars). The term 1.44 expands the diameter of the foundation 20% beyond the tank diameter. The term 0.005 converts from MG to cubic yards.

For elevated steel tanks, footings are defined for each of four legs of the tank:

$$Emissions = \frac{EIOLCAEF*FdtnArea*4*FdtnDepth*ReinConcCost*AnalysisPeriod}{FdtnLife*27}$$

$$Emissions = \frac{EIOLCAEF * FdtnArea * 4 * FdtnDepth * \mathrm{Re}\, inConcCost * AnalysisPeriod}{FdtnLife * 27}$$

Where the "EIOLCAEF", "analysis period", foundation (fdtn) depth", "reinforced concrete (reinconc) cost" and "foundation (fdtn) life" are described above. "Foundation (fdtn) area" is defined on the *Assumptions* worksheet and the default value is 225 square feet per footing for each of 4 footings. The term 27 converts from cubic feet to cubic yards.

Additional Energy and Pipe Production Emissions

Emissions and energy use due to pumping and/or additonal pipe required as a result of installing a tank above or below the system hydraulic grade line are calculated for each chemical *i* as follows:

$$Emissions = \frac{ElectricityUse * ElectricityEF * AnalysisPeriod}{1{,}000{,}000} + \frac{AddedPipe * PipeCost * EIOLCAEF * AnalysisPeriod}{PipeLife * 1{,}000{,}000} + \frac{AddedPipe * FittingCost * EIOLCAEF * AnalysisPeriod}{FittingSpacing * FittingLife * 1{,}000{,}000}$$

Where Electricity Use is the additional annual electricity use in kilowatt-hours entered on the *Tank User Input* worksheet; the Added Pipe is the additional pipe required in feet entered on the same page. The electricity EF is selected based on the state indicated on the *Tank User Input* worksheet. The emision factor is found and can be edited on the *Electricity EF* worksheet. Pipe and Fitting Costs are for 18-in. diameter PVC pipe and are found and can be edited on the *Costs* worksheet. The pipe EIOLCAEF is for the "Plastic pipe, fittings, and solid forms" sector and the fitting EIOLCAEF is for the "Metal pipe, valves, and fittings". Both values can be found and edited on the EIOLCA EFs worksheet. The Pipe Life is assumed to be 60 years, fitting life 40 years. The fitting spacing is assumed to be every 200 feet. The Analysis Period is discussed above.

Appendix E.3:
Pipe Analysis Assumptions

Appendix E.3:
Pipe Analysis Assumptions
Return to Piping User Input
Return to Piping Results

General Pipe Data
Compiled from Mays 200([ref]

Types to Consider	Size	fittings	gaskets	joints	lining	coatings	notes
PVC	4-36"	DI generally	rubber	bell and spigot	none	none	- extruded under extreme heat; sized by dimension ratio - PVC fittings used sometimes for 4-8 in pipe but excluded from analysis
Reinforced Concrete	12-54"; lengths 24-40'	Unknown	Unknown	Unknown	None	None	- can be cylinder, non cylinder, pretensioned, prestressed - assumed pretensioned cylinder, most common in west; prestressed most common elsewhere - made of: cylinder with joint rings; mortar-lined, wrapped with hot-rolled steel bar; covered with cement slurry and dense mortar coating
Ductile Iron	5-54" in 18 ft lengths	DI	rubber, natural or synthetic, 1/8 in thick	push on, mechanical; flanged for valve/fittings	often cement	PE tube 0.008" thick; asphalt 0.001" thick	
Steel	4-144"; pipe 40 ft long	steel; flanged or fabricated	rubber, 1/8" thick	bell and spigot; welded for larger than 24"	often cement; min. in practice	enamel, tape, epoxy, PE coating	- rarely smaller than 16 in.; common in West for >24"
HDPE	4-63"	DI generally	no for thermal fusion	butt fusion; flange; or mechanical	NONE	NONE	-NOT CURRENTLY INCLUDED BECAUSE EIO-LCA DOES NOT DISTINGUISH BETWEEN HDPE AND PVC
Cast Iron	Not commonly used anymore						

Assumptions:

1) valves and fittings are the same for all pipe types
2) PVC and concrete pipe uses cement for bell and spigot joint with gasket; DI uses pushon joint with gasket; steel is welded
2) flange fittings installed manually
3) fusion welding equivalent to welding machine, 2 min per joint; welder = 9600 watts
4) trenching and construction equipment (loader, crane, etc) use are equivalent between alternatives
5) Internal diameter of pipe is equivalent to nominal diameter
6) Mortar lining volume is assumed to be: Nominal pipe diameter * pi() * mortar thickness

Notes:

1) Two scenarios associated with concrete pipe were considered. Pipe was analyzed as part of the "Concrete Product" sector. It was also analyzed assuming 90% concrete and 10% steel.

Scenario 2: Concrete (90% Steel % 10%

Volume of Concrete in Pile Calcs

D	Pipe Volume (cy)	Mortar Volume	Steel Volume	Mortar Cost	Steel Cost	Mortar %	Steel %
36	7.999	7.199	0.800	$ 20.54	$ 2,338.59	0.87%	99.13%

Still, the concrete scenario 2 underestimates effects because it ignores final production of pipe.

Reset Default Pipe Assumption Values

Appendix E.4:
Tank Analysis Assumptions

Appendix E.4:
Tank Analysis Assumptions

Return to Tank User Input
Return to Tank Results

Assumptions

1) Tank appurturances are equivalent for similarly sized tanks. Therefore, pipes, pumps, and valves are not included in the analysis.
2) All tanks are circular. Foundations for ground level tanks are sized to extend 20% beyond the calculated tank diameter.
3) Elevated tank foundations are assumed to be 4 225 225 square feet each.
4) If additional piping is needed for tanks, it is assumed to be 18" PVC with a service life of 60 years. It is assumed that a fitting will be needed once every 200 feet (40 year service life). No additional valves are assumed to be needed.
5) Pumping electricity is calculated assuming pump operation of 50% and pump efficiency of 60%
using the equation: Electricity [kWh/(gal/min)/(ft. head) =
(1/3960 [hp]) / pump efficiency * 0.746 kW/hp * 8760 h/yr * pump operation %

The assumed calculated value is: 1.375202 kWh / (gal/min) / ft

Notes:

A custom sector was created to analyze concrete tanks, assuming 98% concrete and 2% steel.
Relative Cost of Concrete and Steel in Tank Sides

Steel Cost ($/cy)	Steel %	Concrete Cost ($/cy)	Concrete %	Cost per cy	Concrete Cost %	Steel Cost %
$ 2,923.44	2%	$ 59.02	98%	$ 116.31	49.7%	50.3%

Assume tank costs are 50% ready-mixed concrete and rebar.

Reset Default Tank Assumption Values

Appendix F: Task 6

Appendix F.1: Summary of Residential Indoor Calculations **F-2**

Appendix F.2: Summary of Commercial Calculations **F-7**

Appendix F.3: Summary of Outdoor Calculations **F-8**

Appendix F.1:
Summary of Residential Indoor Calculations

General Assumptions:

Functional Unit	l/yr	365000	annual equivalent to 1000 l/d
Analysis Period	yr	20	
Conversion Factor	l/gal	3.7854	

[A] General equation for calculating fixtures needed [#] (Tables X-X):

$$\frac{FunctionalUnit * ConversionFactors * AnalysisPeriod}{AnnualWaterUse * No.HHFixtures * FixtureServiceLife}$$

[B] Equation for calculating material production emissions [g or MJ] for each species (Table X):

$$PurchasePrice * PriceReduction * [A] * LCAEF$$

[C] General equation for calculating the economic costs of fixtures [$]:

$$PurchasePrice * No.Fixtures$$

[D] General equation for calculating the avoided economic cost of water [$]:

$$-(Watersavings * Waterprice) * AnalysisPeriod$$

[E] General equation for calculating the avoided economic cost of energy [$, x is energy source (gas, electricity)]:

$$-(Elecsavings * Elecprice + NGSavings * NGprice) * AnalysisPeriod$$

[F] Equation for calculating environmental costs of fixture production [$]:

$$\frac{\sum_{x-1}^{6}(ProductionResults_x * ECFactor_x)}{1000000}$$

[G] Equation for calculating avoided environmental costs of water production [$/analysis period]:

$$\sum_{x-1}^{6}(MMWDmarginalResults_x * ECFactor_x) * \frac{Timeframe}{1000000}$$

[H] Equation for calculating avoided environmental costs of energy production [$/analysis period]:

$$\sum_{x-1}^{6}(Elecsavings_x * StateEF_{xx} + NGsavings_x * NGcost * LCAEF_x) * ECFactor * \frac{AnalysisPeriod}{1000000}$$

[I] Equation for calculating fixture full purchase costs [$/analysis period]:

$$[C]+[D]+[E]+[F]+[G]+[H]$$

[J] Equation for calculating early replacement costs [$/analysis period]:

$$0.5*[C]+[D]+[E]+0.5*[F]+[G]+[H]$$

[K] Equation for calculating marginal replacement costs [$/analysis period]:
Marginal Cost = Purchase Price- Comparable Fixture Price
Marginal Cost is used in place of purchase price in equations [C] and [F]; results are uesd in [J].

[L] Equation for calculating end-of-life replacement costs [$/analysis period]:

$$[D]+[E]+[G]+[H]$$

Equation Parameters:

Annual water use = gal/hh/yr
No. HH Fixtures = # in home

Purchase Price = $
Water price= $0.96/kl Source:[1]
Price reduction = 90%
LCAEF = g or MJ/$ (emission factor from EIOLCA)
Water savings per fixture = l/yr
Electricity savings = kWh/yr
Gas savings = therm/yr
Electricity price= 0.114 $/kWh
NG price(res cust)=1.30 $/therm
NG cost (procurement) = 0.83 $/therm [PG&E May 07 bill]
Production results = g or MJ calc'd in [B]
External Cost (EC) Factor=$/Mg [Matthews 2001]
MMWD Marginal Results = g or MJ per functional unit

Acronyms:

l	liters
yr	year
gal	gallons
d	day
hh	household
g	gram
MJ	megajoule
LCA	life-cycle assessment
EF	emission factor
Elec	electricity
EC	External Cost
MMWD	Marin Municipal Water District
NG	Natural Gas
gpf	gallon per flush

Fixture Specifc Calculations

Toilets

Fixtures per household	#	2	consistent with Aquacraft studies
Fixture Service Life	yr	25	conservative value; range is 20-40 years

Data (from Aquacraft studies)

	UNITS	Toto Drake	Caroma Caravelle		Niagara Ultimate		Source
Study		Seattle	EBMUD	Seattle[1]	EBMUD	Tampa	
Cost of toilet		$ 280	$ 350	$ 150	$ 165	$ 165	[1], [4-6]
Fixtures Studied	#	34	35	40	32	52	[1], [4-6]
Water savings estimate	gal/hh/yr	11827	25140	15733	25984	27018	[1], [4-6]
Number of Fixtures [A]		13.0	6.1	9.8	5.9	5.7	Calculated
Average # of Fixtures		13.0	8.1		5.8		Calculated

NOTES:

[1] Caroma Caravelle was discounted for the Seattle study; does not reflect the actual purchase price of the toilet.

The EBMUD study also examined a pressure-assist toilet utilizing Sloan Flushmate 1.1 insert. In the Aquacraft study, the insert was used in St. Thomas Creations pottery but price data was not found for this model. The Sloan Flushmate insert is used in the Kohler Wellworth model. Performance is assumed to be identical. However, because only 2 of these models were used in the EBMUD study, Aquacraft did not report results for the performance based on the trace study. Instead, the following calculations were used to establish the annual water savings associated with this toilet model.

Kohler Wellworth

Cost ($) based on internet search

Flush volume (gpf) 1.1 unconfirmed manufacturer's estimate

Water use(gal/toilet/yr) used was calculated pre-retrofit and post-retrofit using:

$$FlushVolume(gal / flush) * No.Flushes(flush / hh / day) * 365 day / yr$$

		Pre	Post	Savings (Pre - Post)
Flush volume	gpf	3.88	1.1	
No. flushes	#/hh	14.1	14.9	
Water use, excludes leaks	gal/hh/yr	19968.42	5982.35	13986

Average ratio of reported savings (with leaks) to calculated savings (as above) = 2.1667 for other models

Water savings estimate	gal/hh/yr	30303.3182
Number of Fixtures		5.1

Showerheads

Fixtures per home	#/hh	2	assumed but consistent with Aquacraft studies
Fixture Service Life	yr	12.5	assumed; consistent with an 8% replacement rate [WNWN]

Data (from Aquacraft studies)

	UNITS	AM Conser-vation Spoiler	Brasscraft LF	Niagara Earth	Niagara Earth hand-held	Source
Study		EBMUD	Seattle	Tampa	Tampa	
Cost of showerhead		$ 14	$ 18	$ 17	$ 30	[1], [4-6]
Fixtures Studied	#	57	51	42	9	[1], [4-6]
Average rated water flow	gpm	2.5	2.5	1.75	2.35	
Average actual water flow	gpm	1.88	1.81	1.73	1.8	[1]; tampa #s assumed
Water savings estimate	gal/hh/yr	1100	730	2941	2826	[1]; Tampa calcs below
Number of Fixtures		280.503562	422.677	104.92	109.16529	Calculated

Showerheads (continued)

Allocated water savings from Tampa results for N. Earth (1.75 gpm) and N. Earth Handheld (2.35 gpm) by assuming that flow rates for the 2.35 gpm model will be similar to but slightly lower than rates for the 2.5 gpm model. The flow rate for the 1.75 gpm model was established such that the weighted average of the two models was equivalent to the reported value of 1.74 gpm. Further calcs to get annual savings:

Tampa total savings	2920	gal/hh/yr [A]			
Tampa savings / fixture	1460	gal/fixture/yr [B] = A/2			
	# units [C]	Actual flow ra [D]	Average ' [F]= E/D	Fixture s [G]=F*B	Household savings [H]= F*A
1.75 gpm Niagara Earth	42	1.73	*101%*	1470.4	*2941*
2.35 gpm N.E. Handheld	9	1.8	*97%*	1413.2	*2826*
Weighted Average	*[E]* =	1.74			2921

The hot water analysis by Aquacraft indicated that the installation of showerheads did not reduce overall hot water use. As a results, no energy analysis was conducted on this point.

Faucets

Two types of faucet improvements were analyzed- aerators/flow restrictors and hands-free devices that prevent water from running when not needed.

Aerators

Because Aquacraft's water trace software could not distinguish between aerators with different flowrates. As a result, specific models cannot be compared. Instead the analysis focuses on the effects of installing faucet aerators thoughout a household.

Fixture Service Life yr 3

	UNITS	New Resources	Niagara	Source
Study		Seattle	Tampa	
Aerator cost (hh total)		$ 3	$ 6	[1], [4-6]
Fixtures Studied	#	87	64	[1], [4-6]
Water savings estimate	gal/hh/yr	1099	3632	[1], [4-6]
Number of Fixtures		584.9	177.0	Calculated

Hands free

	UNITS	Hands free controller[1]	Delta eFlow	Source
Study		Tampa	Tampa	
Fixture Service Life		10	15	assumed based on internet search
Aerator cost (hh total)		$ 290	$ 317	[1], [4-6]
Comparable fixture cost		--	$ 119	[1]
Fixtures Studied	#	17	2	[1], [4-6]
Water savings estimate	gal/hh/yr	532.9	3003	[1], [4-6]
Number of Fixtures		361.9	42.8	Calculated

Note:

1 This fixture can be used with or without aerators or other conservation devices. It consists of a pedal or bar that is used to stop and start flow, preventing water from flowing when not in use. Aquacraft estimates the bar saves an additional 0.5 gal/person/day beyond other measures; the Tampa study had an average occupancy of 2.92 people per home. The simplicity of the device indicates that the production costs are less than 60% of the consumer costs. The producer costs are assumed to be 20% of consumer costs.

Faucets (continued)

Hot water Energy Savings Calculations

In the EBMUD and Seattle studies, Aquacraft tracked the use of hot water to examine how water heating was affected by retrofit programs. Reduced hot water use has energy implications. Hot water use was reduced by faucet retrofits in the EBMUD and Seattle studies. The results reported in the original utility-specific studies (sources [4] and [6]) were not the same as those reported in the summary report [1]. The average results of these studies were used to allocate the Tampa faucet results to estimate the reduced use of hot water in these studies.

Hot Water Energy savings- Aquacraft results

Source		EBMUD [6]	Seattle [4]	EBMUD [1]	Seattle [1]	*AVG*	*% of total use that is hot*
Count	#	10	10				
Avg Occupancy	people/hh	2.74	2.51				
Total water pre	g/hh/d	28.77	23.092			25.931	
Total water post	g/hh/d	28.77	20.08			24.425	
Hot water Pre	g/hh/d	23.564	21.586	19.2	18.8	20.788	80%
Hotwater post	g/hh/d	16.988	19.327	12.9	17.3	16.629	68%
Savings	g/hh/d	6.576	2.259	6.3	1.5	4.1588	
Reduction		28%	10%	33%	8%	0.1979	
Difference	g/hh/y	2400.24	824.535	2299.5	547.5	1517.9	
Annual elect saving	kWh/yr	56.9089161	19.5495	53.873	12.981048	35.99	
Annual gas saving	therm/yr	114.721871	39.4095	89.797	26.16831	72.552	

Equation for Electricity Savings (kWh/yr)

$$\frac{Hotsavings*0.00378*1000*1000*25*4.2}{3.6*10^{\wedge}6*0.93}*0.2$$

Natural Gas Savings (therm/yr)

$$\frac{Hotsavings*0.00378*1000*1000*25*4.2*0.03414}{3.6*10^{\wedge}6*0.65}*0.8$$

Assumes:

Heater efficiency: 93%-electric and 65%-gas

20% of water heaters are electric; 80% gas

Hot water savings = gal/yr

0.00378 m3/gallon	25 deg C
1000 kg/m3	4.2 J/g/deg C
1000 g/kg	0.03414 therm/kWh
25 deg C	1 kWh/(3.6*10^6) J

Hot Water Energy savings- Tampa estimates

Tampa Avg Occupancy 2.92 people/hh

		Eflow	Aqualean	Niagara	
Total pre volume	g/hh/d	27.448	1.5	27.448	[1]
Total post volume	g/hh/d	19.2136	0.0	18.104	[1]
Estimate hot pre	g/hh/d	22.0	1.2	22.0	[Pre * % of pre-total that is hot]
Estimated hot post	g/hh/d	13.1	0.0	12.3	[Post * % of post-total = hot]
savings	g/hh/yr	3256.8	427.2	3532.6	{Pre hot - Post hot]*365
Annual elect saving	kWh/yr	77.2183196	10.12871528	83.755794	
Annual gas saving	therm/yr	155.663307	20.41833244	168.84211	

Washing Machines

Fixtures per home	#/hh	1	assumed
Fixture Service Life	yr	13	[1]

Washing Machines (continued)
Data (from Aquacraft studies)
Machines used in a single study

Types:		Maytag Neptune	Fisher/Paykel Ecosmart	Whirlpool Duet	Whirlpool Calypso	
Study		Seattle	EBMUD	Tampa	Tampa	Sources:
Washing machine cost		1066	749	999	899	[1], [4-6]
Comparable mach cost	years	550	375	500	500	[1], [4-6]
Fixtures Studied	#	12	13	16	10	[1], [4-6]
Water savings estimate	gal/hh/yr	4264	4189	8004	6208	[1], [4-6]
Number of Fixtures	#	34.8	35.4	18.5	23.9	Calculated
Electricity Savings[1]	$/yr	36.4	36.4	193.0	193.0	[7]
Gas Savings[1]	$/yr	27.7	27.7	12.8	12.8	[7]

Note:
[1] Electricity and gas savings were calculated using EPA's Energy Star tool (EPA 2007), using PG&E's May 2007 prices for gas and electricity. Calculations assume 80% of fixtures needed are served by gas water heaters and the remaining have electric water heaters.

Machines used in multiple studies. Units, sources, and notes are the same as above.

Types:	Frigidaire Gallery			Whirlpool Super Capacity			
Study	Seattle	EBMUD	*Average*	Seattle	EBMUD	*Average*	Sources:
Fixtures Studied	23	9		2	11		
Washing machine cost	690	699	*$ 693*	555	550	*$ 551*	[1], [4-6]
Comparable mach cost	495	500	*$ 496*	489	489	*$ 489*	[1], [4-6]
Water savings estimate	5535	6059	*5682*	5610	4712	*4850*	[1], [4-6]
Number of Fixtures	27	24	*26*	26	31	*31*	Calculated
Electricity Savings[1]	207	193	*203*	207	205	*206*	[7]
Gas Savings[1]	14	13	*13*	14	14	*14*	[7]

Sources:

1 Aquacraft (2005). Water and Energy Savings from High Efficiency Fixtures and Appliances in Single Family Homes: Volume 1. Boulder, Colorado.

2 Gleick, P. H., D. Haasz, et al. (2003). Waste Not, Want Not: The Potential for Urban Water Conservation in California. Oakland, California, Pacific Institute for Studies in Development, Environment, and Security**:** 176.

3 Matthews, H. S., Hendrickson, C., and Horvath, A. (2001). "External Costs of Air Emissions from Transportation." Journal of Infrastructure System **7**(1): 13.

4 Mayer, P., W. B. DeOreo, et al. (2000). Seattle Home Water Conservation Study: The Impacts of High Efficiency Plumbing Fixture Retrofits in Single Family Homes. Boulder, Colorado, Aquacraft, Inc.

5 Mayer, P., W. B. DeOreo, et al. (2004). Tampa Water Department Residential Water Conservation Study: The Impcts of High Efficiency Plumbing Fixture Retrofits in Single-Family Homes, Aquacraft, Inc. for USEPA and Tampa Water Department.

6 Mayer, P. W., W. B. DeOreo, et al. (2003). Residential Indoor Water Conservation Study: Evaluation of High Efficiency Indoor Plumbing Fixture Retrofits in Single-Family Homes in the East Bay Municipal Utility District Service Area. Boulder, Colorado, Aquacraft, Inc. for US Environmental Protection Agency and EBMUD**:** 172.

7 Energy Star Program. (2007). "Life-cycle Cost Estimate for Energy Star Qualified Residential Clothes Washers." Updated July 2007. Retrieved October 7, 2007, from http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/CalculatorConsumerClothesWasher.xls.

Appendix F.2:
Summary of Commercial Calculations

Office building located in Oakland, Ca

Stories	15		toilet life	25
Useable space/floor	6000	sf	urinal life	20
Kitchen sinks/floor	2		Installation cost	$100
Bathroom sink/floor	6		Work days per year	245
Toilets per floor	8			
Urinals per floor	2		Check (assume 30% common space)	
Employees per floor	150		28 sf per employee -- OKAY	
Toilet use per person	2	flushes (3-women, 1-men; assume even employees) [Vickers]		
Urinal use per person	1	flushes (2 men, 0 women) [Vickers]		

	Toilets			Urinals			
	Old (pre-94)	Toilet 1	Toilet 2	Old (pre-94)	Urinal 1	Urinal 2 (liquid)	Urinal 2 (w/out liquid)
Water use (gpf)	3.5	1.60	1	1.5	1	0	0
Water use (gpd)	15750	7200	4500	3375	2250	0	0
Water use (kl/y)	14309	6541	4088	3066	2044	0	0
Water savings (gpd)	--	8550	11250	--	1125	3375	3375
Annual savings (kl/yr)	--	7768	10221	--	1022	3066	3066
Cost savings ($/yr)	--	$ 7,511	$ 9,883	--	$ 988	$ 2,965	$ 2,965
Fixtures needed for kl/d	--	46.99	35.71	--	357.12	119.04	119.04
Purchase costs ($)	--	$6,203	$12,571	--	$89,281	$53,568	$53,568
Installation costs ($)	--	$3,759	$2,857	--	$35,712	$11,904	$11,904
Trap seal liquid ($/yr)*	--	--	--	--	--	$ 2,917	--
Water use (lpf)	13.25	6.06	3.79	5.68	3.79	0	0
Material Production Environmental Effects							
Energy	--	47,636	96,543	--	685,675	1,170,862	411,405
GWP	--	3,323,383	6,735,389	--	47,836,571	66,207,671	28,701,943
Nox	--	5,657	11,464	--	81,424	504,500	48,854
PM	--	901	1,825	--	12,964	429,849	7,778
SOx	--	5,582	11,314	--	80,353	516,399	48,212
VOC	--	3,796	7,693	--	54,640	534,948	32,784
CO	--	31,968	64,789	--	460,152	688,589	276,091

* 3 ounces may be needed after 1500 flushes,cost $20 for a quart, $211 for 12 quarts
quart = 32 oz 10 doses per bottle
http://www.plumbersurplus.com/Prod/Waterless-1114-BlueSeal-Trap-Liquid-1-Quart/26888/Cat/933

Appendix F.3:
Summary of Outdoor Calculations

Key:

[#] indicates a source (see References section)

[X] indicates an equation

Acronyms:

af	acre-foot	hh	household
avg	average	in	inch
COM	commercial	IND	industrial
cy	cubic yard	kl	kiloliter
d	day	l	liters
E0	reference ET for a particular plant in a certain climate; here, summer water ET for turf grass	LCA	life-cycle assessment
		m^2	square meters
EC	External Cost	med	medium
EF	emission factor	MF	multi-family
EIOLCA	economic input-output-based LCA [3]	MJ	megajoule
ET	evapotranspiration	mo	month
g	gram	res	residential
gal	gallons	SF	single-family
gpcpd	gallons per capita per day	sf	square feet
gpd	gallon per day	yr	year

MODEL ASSUMPTIONS

Time frame		20	yrs, selected for assessment
Functional Unit		1000	l/day, selected for assessment
	or	365000	l/yr
Production costs		60%	of purchase costs (for EIOLCA input)

SCENARIO ASSUMPTIONS/EQUATIONS

Average lot size, yard size, irrigated area data from [1], seeTable 12.

Irrigated area % (Irrig%), % of yard that is irrigated, assumptions from [1]:

For average-sized single family homes:	35%
For large-sized single family homes:	10%
For multi-family facility:	25%
For commercial facility:	3%
For industrial facility:	5%

[A] - Irrigated area (sf):

Yard size = m^2, from [1], shown in Table 12

$$IrrigArea = Yardsize * Irrig\%$$

[B]: Annual water ET ($l/m^2/yr$):

E0 assumptions are from [1] and are listed in Table 12 of the text.

Annual water use estimate assumes 4 months (June-Sept) at 100% E0, 5 months (Apr-May, Oct-Dec) at 50% E0, 3 months (Jan-Mar) at 10% E0

$$AnnualET = \sum_{x=1}^{12} E0 * E0\%_x$$

[C]: Total baseline use (l/yr):

Turf % found in Table 12

Turf Mult	1.6	E0 multiplier for turf [1]
(assumes high water plants w/ 50% irrigation efficiency)		
Non-turf mult	1	E0 multiplier for assumed mix of non-turf plants [1]
(assumes 33% of non-turf area are high, low, med plants; w/ 50% irrigation efficiency)		

$$TotalUse = IrrigArea * AnnualET * (Turf\,\% * TurfMult + (1 - Turf\,\%) * NonTurfMult)$$

Baseline use for residences was compared with typical values in [1] to confirm they were reasonable.

Scenario Calculations	SF1- home Berkeley	SF2- home Paso robles	SF3- home Palm Desert	SF4- large home Fresno	MF- Apt building LA	COM- Store, Palm Desert	IND- 10 acre site, Fresno	Source:
average lot (sf)	7800	9000	11000	177558	9464	979200	435602	[1](res); assumed other
yard size (sf)	6019	7700	9900	175058	2704	--	--	[1]; for each zone
Irrigated area (sf)	2107	2695	3465	17506	676	29376	21780	calculated
turf %	70%	75%	80%	90%	0.5	0.5	0.6	assumed
summer water e0 (gal/sf/mo)	2.7	4	5.2	4.5	2.85	5.2	4.5	[1] avg
summer water e0 (l/m2/mo)	110	163	212	183	116	212	183	converted
annual water e1 (l/m2/yr)	748	1,108	1,441	1,247	1,136	1,441	1,247	calculated
turf baseline use (/yr)	163,964	332,947	593,597	2,919,657	856,692	39,669	3,145,291	calculated
turf water %	79%	83%	86%	94%	78%	62%	71%	calculated
Baseline use (l/yr)	207,883	402,311	686,346	3,122,410	1,104,738	64,463	3,430,726	calculated
To check assumptions using general estimates from [1]:								
baseline use (af/yr)	0.168	0.326	0.556	2.531	0.895	0.052	3	calculated
baseline use (af/yr)	0.15	0.25	0.55	0.38	--	--	--	[1]

ALTERNATIVE STARTEGIES ASSUMPTIONS/CALCULATIONS

<u>Turf Maintenance - TM</u>

InitTurfUse	4.5	cy/1000 sf (Initial turf compost use)
YrlyTurfUse	0.56	cy/1000 sf (Annual turf compost use)
TurfApps	19	number of yearly applications over the timeframe
PlantUse	4.8	cy/1000 sf (assumes 80% of non-turf area needs compost)
Price source:	http://www.charmeck.org/Departments/LUESA/Solid+Waste/Compost-Yard+Waste/sales.htm	
Application source:	http://www.earth911.org/master.asp?s=lib&a=organics/composting/comp_applications.asp	
Compost price	$23	per cy
Mulch price	$6	per cy
Mulch life	2	years
TMWater%	10%	[2], percent of expected water reduction

[D]: Compost application for turf (cf over 20 year period):

$$TurfCompost = \frac{(InitTurfUse + TurfApps * YrlyTurfUse) * Turf\,\% * IrrigArea * Convfactor}{1000}$$

[E]: Compost application for landscaping (cf over 20 year period):

$$NonturfMulch = \frac{PlantUse * ConvFactors * (1 - Turf\%) * IrrigArea * Timeframe}{1000 * MulchLife}$$

[F} Maintenance Cost ($ over 20 years)

$$TMCost = (TurfCompost * Compost\Pr ice + NonTurfMulch * Mulch\Pr ice) * ConvFact$$

[G]: Turf Maintenance Water Savings (l/yr):

$$TMSavings = BaselineUse * TMWater\%$$

[H]: Typical households for kl/day (#):

Functional Unit = 365000 l/yr = kl/day

$$TMUnits = 365000 / TMSavings$$

[I]: Total TM Cost ($, shown as purchase costs in Table X):

$$TotalTMCost = TMCost * TMUnits$$

TM Alternative Calcs	SF1	SF2	SF3	SF4	MF	Com	Ind
Compost volume	(cf/hh/20 year period)						
turf applications	180	246	338	1920	41	1790	3180
mulch application	819	873	898	2269	438	19036	11291
Compost costs	cost/20 years						
turf applications	$ 153	$ 210	$ 288	$ 1,636	$ 35	$ 1,525	$ 2,709
mulch application	$ 182	$ 194	$ 200	$ 504	$ 97	$ 4,230	$ 2,509
total	$ 335	$ 404	$ 487	$ 2,140	$ 132	$ 5,755	$ 5,218
WATER SAVINGS							
Savings (l/yr)	20788	40231	68635	312241	6446	511110	343073
Savings (kl/day)	0.06	0.11	0.19	0.86	0.02	1.40	0.94
HH units for kl/d	18	9	5	1	57	1	1
TOTAL COSTS per kl/day over 20 years							
$	5884	3665	2592	2502	7499	4110	5552

[J]: EIOLCA TM Results (g, MJ) for environmental effect X, in Table X:

EIOLCA sector: Fertilizer, mixing only, manufacturing

$EIOLCAEF_x$ = EIOLCA Emission factor for effect X, given the appropriate sector, shown in Table X

$$TMEIOLCA_x = 60\% * TotalTMCost * EIOLCAEF_x$$

[K]: Water Savings Cost Offset for all alternatives ($, shown in Table X)

Water Cost 0.000967 $/liter

$$WaterSavingsCost = WaterCost * 365000 * Timeframe$$

[L]: TM Production Costs ($, shown in Table X):

$ExtCostFactor_x$ = External cost for effect X, shown in Table X, $/Million grams

$$ExtCostTotal = \frac{\sum_x TMEIOLCA_x * ExtCostFactor_x}{1000000}$$

[M]: Water Supply External Costs for all alternatives ($, shown in Table X):

WaterLCAEF = Effects for water supply system, shown in Table X

$$ExtWaterTotal = \frac{\sum_x WaterLCAEF_x * ExtCostFactor_x}{1000000}$$

Drip Irrigation- DI

Price source: RS Means Landscape and Site Works Data 1994

DI system price $1.05 $/sf

Component:	Sector%	Sector
Tubing	85%	Plastics pipe, fittings, and profile shapes
Screens/filters	3%	Steel wire drawing
Control equip.	5%	Watch, clock, and other measuring and controlling device manufacturing
Valves	7%	Metal valve manufacturing

Tubing life 3 years [Wikipedia, 10/07]

System life 20 years, assumed

TMWater% 50% [2], only for landscaped area (not turf), percent of expected water reduction

[N]: DI Area Size:

$$DIArea = (1 - Turf\%) * IrrigArea$$

[O]: DI System cost:

$$DISectorCost = DI\,Price * DIArea * Sector\%$$

[P] DI EIOLCA Results (Table X):

$$DIEIOLCA_x = \sum_z 60\% * SectorCost_z * EIOLCAEF_{z,x}$$

Other calculations for drip irrigation are similar to those shown in Equations G, H, I, K, L, and M.

DI Alternative Calculations

Costs	SF1	SF2	SF3	SF4	MF	Com	Ind
irrigation size (sf)	632	674	693	1,751	338	14,688	8,712
irrigation cost ($)	$ 664	$ 707	$ 728	$ 1,838	$ 355	$ 15,422	$ 9,148
Tubing	$ 564	$ 601	$ 619	$ 1,562	$ 302	$ 13,109	$ 7,775
Screens	$ 20	$ 21	$ 22	$ 55	$ 11	$ 463	$ 274
Controls	$ 33	$ 35	$ 36	$ 92	$ 18	$ 771	$ 457
Valves	$ 46	$ 50	$ 51	$ 129	$ 25	$ 1,080	$ 640

WATER SAVINGS

baseline use non-turf (l/yr)	43,919	69,364	92,749	202,754	24,793	1,965,807	1,009,037
Water savings (l/yr)	21,959	34,682	46,375	101,377	12,397	982,903	504,519
Savings %	11%	9%	7%	3%	19%	19%	15%
KL/DAY	0.06	0.10	0.13	0.28	0.03	2.7	1.4
Units for kl/day	17	11	8	4	29	0.4	0.7

TOTAL COSTS

$ (total)	$ 64,158	$ 43,306	$ 33,313	$ 38,495	$ 60,781	$ 33,313	$ 38,495
Tubing	$ 62,503	$ 42,190	$ 32,454	$ 37,502	$ 59,213	$ 32,454	$ 37,502
Screens	$ 331	$ 223	$ 172	$ 199	$ 313	$ 172	$ 199
Controls	$ 551	$ 372	$ 286	$ 331	$ 522	$ 286	$ 331
Valves	$ 772	$ 521	$ 401	$ 463	$ 731	$ 401	$ 463

Smart Controllers

Assumed the basic irrigation system is already in place. System is for on-site controllers (e.g., moisture sensors) because satellite controlled systems are expensive, more than 3 times more expensive than on-site systems. The number of sensors (Sensor#) per home is assumed: 4 for an average home, 7 for large lot, 2 for MF, 10 and 8 for commercial and industrial, respectively.

Price source:	[2]	
Controller price	$289.08	$/unit, cost is $26 per year over 15 years at 4% amoritization rate
EIOLCA sector:	Watch, clock, and other measuring and controlling device manufacturing	
System life	15	years
TMWater%	15%	[2]

[Q]: System cost:

$$SCCost = Sensor\#*Sensor\ \mathrm{Pr}ice$$

Calculations for smart controllers are similar to those shown in Equations G - M.

SC Alternative Calcs	SF1	SF2	SF3	SF4	MF	Com	Ind
SENSOR COSTS	Number of sensors needed is assumed						
Sensors needed	4	4	4	7	2	10	8
Sensors cost ($)	1156	1156	1156	2024	578	2891	2313
WATER SAVINGS							
Water savings (l/yr)	623,649	1,206,932	2,059,038	9,367,231	193,389	15,333,292	10,292,179
KL/DAY	0.09	0.17	0.28	1.28	0.03	2.10	1
Units for kl/day	12	6	4	1	38	0.5	0.7
TOTAL COSTS							
$	18047	9325	5466	2103	29099	1835	2187.05343

Rain Barrel Catchment (RBC)

Price source: http://www.lid-stormwater.net/raincist/raincist_cost.htm#2

Storage system	Material	per cy	Gallons	Cost($)
Avg residence	Polyethylene		2,000	$950
Large residence	Reinf. Concrete		3,000	$1,000
Commercial	Reinf. Concrete		12,000	$4,000
Industrial	Reinf. Concrete		9,000	$3,000

Sector

Polyethylene: Plastics plumbing fixtures & all other plastics products

Reinforced Concrete (cost per 3,000 gal.; does not include labor)

Material	% cost	Sector
Lumber	10%	Sawmills
Concrete	60%	Ready-mix concrete manufacturing
Rebar/mesh	10%	Fabricated structural metal manufacturing
Latex seal	5%	Paint and coating manufacturing
Lid and hatches	5%	Fabricated structural metal manufacturing
Pipe, accessories	10%	Plastics pipe, fittings, and profile shapes

Water Parameters

Period	E0%	#Months	Rainfall (in/yr) Berkeley	Paso Robles	Palm Desert	Fresno	LA
Jan-March	0.1	3	13.96	8.36	1.93	6.48	10.15
Apr-May	0.5	2	2.24	0.91	0.12	1.15	1.14
Jun-Sept	1	4	0.67	0.45	0.52	0.51	0.52
Oct-Dec	0.5	3	8.53	2.86	0.58	3.09	3.33

[R]: Seasonal water requirements for period Y (gal):

$$SeasonWaterReq = IrrigArea * E0 * \%E0 * No.Months$$

$$AnnualWaterReq = \sum_{y=1}^{4} SeasonWaterReq$$

[S]: Seasonal water from rainfall (gal):

Rainfall Efficiency (%): 60% remainder runs off and is not used by landscape

$$RainfallVol = Rainfall / 12 * RainEff * IrrigArea * ConvFactors$$

In this equation, area is in sf, rainfall in in/yr.

[T]: Seasonal Water Availability (gal):

$$WaterAvailability = RainfallVol - AnnualWaterReq$$

A negative value indicates a shortage. The sum of seasonal water shortage is the annual shortage.

[U]: Seasonal collection potential (gal):

Catchment Efficiency 90% assumed

$$RoofArea = LotSize - YardSize$$ (sf, values are in Assumptions table above)

$$CollectPotential = RoofArea * Rainfall / 12 * CatchmentEff * ConvFactor$$

The sum of the seasonal collection potential is the annual potential.

[Z]: Calculated seasonal savings (gal and l):

If water availablity is positive (no shortage), savings equals two times the storage capacity (assumed to be used between rainfall)

If water availability is negative (shortage), if shortage magnitude is greater than collection potential, savings equals collection potential.

If water availability is negative (shortage), if shortage magnitude is less than collection potential, savings equals requirements plus the storage volume.

Household units are calculated as in [H]., Total costs are calculated for each material as in [I] in turf maintenance section. The purchase costs are the sum of the total costs for each material.

RWC Alternative Calcs	SF1	SF2	SF3	SF4	MF	Comm.	Ind
WATER AVAILABLE							
Water needed (gal)							
Jan-Mar	1706	3234	5405	23633	578	45827	29403
Apr-May	5688	10780	18018	78776	1927	152755	98010
Jun -Sept	22752	43120	72072	315104	7706	611021	392042
Oct-Dec	8532	16170	27027	118164	2890	229133	147016
Annual	38678	73304	122522	535677	13101	1038735	666471
Rainfall (in/yr)	Berkeley	Robles	Palm Desert	Fresno	LA	Palm Desert	Fresno
Jan-Mar	14.0	8.4	1.9	6.5	10.2	1.9	6.5
Apr-May	2.2	0.9	0.1	1.2	1.1	0.1	1.2
Jun -Sept	0.7	0.5	0.5	0.5	0.5	0.5	0.5
Oct-Dec	8.5	2.9	0.6	3.1	3.3	0.6	3.1
Annual	25.4	12.6	3.2	11.2	15.1	3.2	11.2
Water from rain in yard (gal)							
Jan-Mar	10998	8426	2501	42422	2566	21203	52780
Apr-May	1765	917	155	7529	288	1318	9367
Jun -Sept	528	454	674	3339	131	5713	4154
Oct-Dec	6720	2882	752	20229	842	6372	25168
Difference in need and rainfall							
Jan-Mar	9292	5192	-2904	18790	10586	1988	-24624
Apr-May	-3923	-9863	-17863	-71247	-23754	-1638	-151437
Jun -Sept	-22224	-42666	-71398	-311766	-104372	-7575	-605308
Oct-Dec	-1812	-13288	-26275	-97935	-30553	-2048	-222761
Annual	-18667	-60625	-118441	-462158	-148093	-9273	-1004130
Max collection (gal)							
Roof size	1781	1300	1100	2500	1670	6760	979200
Jan-Mar	13947	6096	1191	9088	7198	38490	1060129
Apr-May	2238	664	74	1613	1035	4323	65915
Jun -Sept	669	328	321	715	504	1972	285631
Oct-Dec	8522	2086	358	4333	3528	12628	318588
Calc savings (gal)							
Jan-Mar	4000	4000	1191	6000	4000	4000	26624
Apr-May	2238	664	74	1613	1035	3638	65915
Jun -Sept	669	328	321	715	504	1972	285631
Oct-Dec	3812	2086	358	4333	3528	4048	224761
Expected water savings (gal)	10719	7077	1944	12661	9066	13658	602930
Savings (%)	20%	7%	1%	2%	3%	80%	45%
WATER SAVINGS							
Water savings (l/yr)	40572	26788	7357	47923	51697	2282091	1404656
KL/DAY	0.11	0.07	0.02	0.13	0.14	6	4
Units for kl/day	9	14	50	8	7	0	0

TOTAL COSTS							
Plastic drum	$ 17,093	$ 25,888	$ 94,264	$ -	$ 13,415	$ -	$ -
Sawmills				$ 508		$ 64	$ 78
Concrete				$ 3,047		$ 384	$ 468
Structural Metal				$ 762		$ 96	$ 117
Latex seal				$ 254		$ 32	$ 39
Plastic pipe				$ 1,922		$ 245	$ 302
Purchase Costs	$ 17,093	$ 25,888	$ 94,264	$ 4,570	$ 13,415	$ 576	$ 702

[AA]: EIOLCA TM Results (g, MJ) for environmental effect X, in Table X:

EIOLCA sectors are listed in table above

$EIOLCAEF_x$ = Emission factor for effect X for material Z, given the appropriate sector (EFs in Table X)

$$RWCEIOLCA_x = \sum_z 60\% * TotalCost_z * EIOLCAEF_{z,x}$$

Equations K, L, and M are models for how water savings costs, prodcution external costs, and water external costs are calculated in Table X.

Greywater Reuse (GR)

Price source:	http://www.thenaturalhome.com/greywaterfilter.htm				
Design Source:	Create an Oasis with Greywater by Art Ludwig				
Greywater capture %	80%				
System life:	20 years, assumed				
Parts (years)	Filter life:	3	Pump life:	10	
	valve life:	15	Pipe life	15	
Greywater Production	Avg. SF	MF	Comm	Ind	
People per day	2.1	30	3500	250	building occupants (#/day)
Production (gpcpd)	25	12	0.1	8.0	
Daily Volume (gpd)	42	288	280	1,600	

Assumes complete capture of grey water.

Material	Sector
Valves	Metal valve manufacturing
Pipe, accessories	Plastics plumbing fixtures & all other plastics products
Filters	Sand and Gravel
Barrels	Plastics plumbing fixtures & all other plastics products

Cost assumptions for each component are shown in the table below.

Rainfall vs. need data are from RBC scenario (Equation S).

[AB]: Seasonal Water Savings per period:

$$SeasSvg = DailyVol * \# days$$

days in the relevant period

Calculated savings are determined as in Equation Z. Other calcs as shown in equations H-M.

GR Alternative Calcs	SF1	SF2	SF3	SF4	MF	Com	Ind
Difference in need and rainfall (gal) [FROM RBC Calcs]							
Jan-Mar	9292	5192	-2904	18790	1988	-24624	23377
Apr-May	-3923	-9863	-17863	-71247	-1638	-151437	-88644
Jun -Sept	-22224	-42666	-71398	-311766	-7575	-605308	-387888
Oct-Dec	-1812	-13288	-26275	-97935	-2048	-222761	-121847
Annual	-18667	-60625	-118441	-462158	-9273	-1004130	-575001

Seasonal Water savings (gal)							
Jan-Mar	3780	3780	3780	3780	25920	25200	144000
Apr-May	2562	2562	2562	2562	17568	17080	97600
Jun -Sept	5124	5124	5124	5124	35136	34160	195200
Oct-Dec	3822	3822	3822	3822	26208	25480	145600
Calc savings (gal)							
Jan-Mar	250	250	3154	250	750	25624	500
Apr-May	2562	2562	2562	2562	2388	17080	89144
Jun -Sept	5124	5124	5124	5124	8325	34160	195200
Oct-Dec	2062	3822	3822	3822	2798	25480	122347
Total Savings	9998	11758	14662	11758	14261	102344	407191
Savings %	18%	11%	8%	1%	84%	8%	45%
Costs							
barrels	$150	$150	$150	$150	$500	$900	$400
filter	$75	$75	$75	$75	$400	$700	$250
piping	$1,500	$1,500	$1,750	$2,000	$3,000	$3,500	$2,500
valves	$150	$150	$200	$275	$500	$800	$650
WATER SAVINGS							
Water savings (l/yr)	37,842	44,504	55,498	44,504	53,979	387,372	1,541,217
KL/DAY	0.1	0.1	0.2	0.1	0.1	1.1	4.2
Units for kl/day	9.6	8.2	6.6	8.2	6.8	0.9	0.2
TOTAL COSTS							
barrels	$1,447	$1,230	$987	$1,230	$3,381	$848	$95
filter	$4,823	$4,101	$3,288	$4,101	$18,032	$4,397	$395
piping	$19,291	$16,403	$15,346	$21,871	$27,047	$4,397	$789
valves	$1,929	$1,640	$1,754	$3,007	$4,508	$1,005	$205
Total	$27,490	$23,374	$21,375	$30,209	$52,968	$10,647	$1,484

Xeriscaping (XS)

Price source:	Vickers 2001
System life:	20 years
Turf costs:	2.5 $/sf
Non-turf costs:	2 $/sf (assumed based on experience)
Revised turf %:	30% revised
EIOLCA sector	Landscaping, nursery
Water reduction	39%

% non-turf area which can remain as low water (LW%) 33%
Assumed % of irrigated area with already low water plants (33% of plants in 20% of area)
Assume other irrigation systems remain the same

[AC]: Landscaping Costs:

$$XSCost = TurfCost + NonturfCost$$

where:

$$TurfCost = IrrigArea * \mathrm{Re}\,vTurf\% * TurfCost$$

$$NonTurfCost = IrrigArea * (1 - \mathrm{Re}\,vTurf\%) * NonturfCost - IttirAgea * (1 - Turf\%) * LW\%$$

Remaining equations are shown above.

Xeriscaping Calculations

<u>Landscaping costs</u>	SF1	SF2	SF3	SF4	MF	Com	Ind
Turf costs	$ 1,580	$ 2,021	$ 2,599	$ 13,129	$ 507	$ 22,032	$ 16,335
Non-turf costs	$ 2,102	$ 2,870	$ 3,922	$ 22,162	$ 493	$ 21,444	$ 18,818
Total	$ 3,682	$ 4,891	$ 6,521	$ 35,292	$ 1,000	$ 43,476	$ 35,153
<u>WATER SAVINGS</u>							
Water savings (l/yr)	81,421	157,572	268,819	1,222,944	25,248	2,001,846	1,343,701
Units for kl/day	4	2.3	1.4	0.3	14.5	0.2	0.3
<u>TOTAL COSTS</u>							
$	$ 16,508	$ 11,331	$ 8,854	$ 10,533	$ 14,464	$ 7,927	$ 9,549
<u>Water Savings calculations</u>							
Use(l/yr)	111,261	210,866	352,448	1,540,930	37,686	2,988,026	1,917,171
Savings	96,622	191,444	333,898	1,581,481	26,777	2,123,071	1,513,556
Percentage saved	46%	48%	49%	51%	42%	42%	44%

<u>Water pricing (WP)</u>

Price and reduction source: Renwick 1998

Water reduction 4% for outdoor water use

Remaining equations are shown above.

<u>WATER SAVINGS</u>	SF1	SF2	SF3	SF4	MF	Com	Ind
Water savings (l/yr)	8107	15690	26767	121774	2514	199333	133798
KL/DAY	0.02	0.04	0.07	0.33	0.01	0.55	0.37
Units for kl/day	45	23	14	3	145	2	3

Dormant turf, no landscape change

Offset: water, energy, fertilizer

Water reduction (%) years, assumed

<u>WATER SAVINGS</u>	SF1	SF2	SF3	SF4	MF	Com	Ind
Water savings (l/yr)	187095	362080	617711	2810169	58017	4599988	3087654
KL/DAY	0.51	0.99	1.69	7.70	0.16	13	8
Units for kl/day	2	1	1	0	6	0.08	0.12

REFERENCES

[1] Hanak, E. and M. Davis (2006). "Lawns and Water Demand in California." <u>California Economic Policy</u> **2**(2): 24.

[2] Gleick, P. H., D. Haasz, et al. (2003). Waste Not, Want Not: The Potential for Urban Water Conservation in California. Oakland, California, Pacific Institute for Studies in Development, Environment, and Security**:** 176.

[3] www.eiolca.net developed by Carnegie Mellon University Green Design Institute. Accessed 7/2007.

Appendix G: Task 8

Appendix G.1: Northern California Workshop- LCA for Water & Wastewater Systems: An Introductory Workshop

Appendix G.2: Southern California Workshop- LCA for Water & Wastewater Systems: Workshop Slides

Appendix G.1: Northern California Workshop- LCA for Water & Wastewater Systems: An Introductory Workshop

WEBCAST

UCBWaterLCA@gmail.com

If you are on the webcast, please email to let us know you are participating.

You may also submit questions (email or chat) to the same address. Include "Question" in the subject line. Unfortunately, we can not guarantee a response during the workshop.

Note: This email address may not be checked regularly after today.

Life-cycle Assessment for Water & Wastewater Systems: An Introductory Workshop

Dr. Jennifer Stokes and Prof. Arpad Horvath
Civil and Environmental Engineering
UC Berkeley

December 8, 2009

Image from: http://www.idswater.com/

Workshop Outline

- Sustainability:
  - What is it? Why do we care?
  - What can we do about it?
- Introduction to LCA
- Interactive LCA Example
- LCA Applied to Water and Wastewater Utilities
- WEST/WWEST
- Conclusions and Recommendations
- Questions and discussion

Thanks to…

- National Science Foundation Graduate Fellowship Program
- University of California Toxic Substances Research and Teaching Fellowship
- California Energy Commission Energy Research Grant [CIEE AWARD No. MR-06-08]

Sustainability:

What is it and why do we care?

A Grand Vision: Sustainable Development

- Definition: Meeting the needs of the current generation without sacrificing the ability of the future generations to meet their needs. (Brundtland Commission, 1987)
- Myriad alternative processes, materials, designs
  - Examine the environmental implications of each
    - Ask relevant questions and come up with metrics
    - Assess a broad range of environmental effects
  - Need economy-wide, life-cycle perspective
  - Need *progress*, not *growth*

Triple Bottom Line for Sustainability of Infrastructure

- Environmental: natural systems, public health
- Economic: job creation, investments, taxes, public and private services
- Social: safety, equity, civil rights, justice, security, …

What Are The Goals?

- Maintain societal progress while improving environmental quality and quality of life
- Environmental goals
  - reduce non-renewable resource use
  - manage renewable resource use for sustainability
  - reduce toxic substance emissions (heavy metals, solvents, ozone depleting substances)
  - reduce greenhouse gas (GHG) emissions
- Educate the stakeholders
- Do good by doing well
  - profit = revenue - cost

Webcast questions?
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Sustainability: What can we do about it?

First, make sure we understand the problem…

Infrastructure & the Environment

- A total of 2.8 billion Mg of different materials used in the U.S. in 1995 (USGS)
  - 81% by volume were construction materials, mostly stone, sand and gravel
- 25% of virgin wood demand by construction (World Watch Institute, 1995)
- In the U.S., buildings account for
  - 65% of electricity consumption
  - 30% of GHG emissions
  - 30% of raw material use
  - 30% of waste output
  - 12% of potable water consumption
- 12 billion Mg of concrete used annually worldwide
- Apparent flows substantial; non-apparent flows are even larger

Water and the Environment

- Capital spending for water infrastructure is estimated to be \$154 - 446 billion between 2000 and 2019 [EPA 2002]
- 2-3% of global energy is used for water and wastewater services; will grow by 33% in next 20 years [ASE 2002]
- One-third of the world lives in nations experiencing water shortages; need 25% more water in the next century to meet global demand [World Bank 2001]
- Eight western states have "substantial" or "high" probability of water shortages by 2025 [USDOI 2003]
- No comprehensive study of the environmental effects of U.S. urban water systems has been conducted…

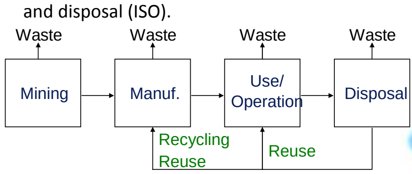
DISCUSSION: What barriers prevent the water industry from doing more to promote sustainability?

Intro to Life-cycle Assessment: An Overview

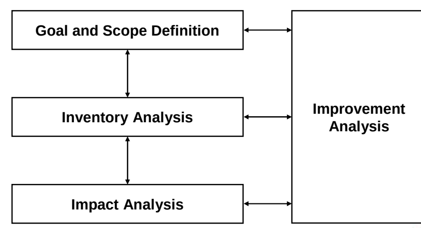
http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

Life-cycle Assessment (LCA)

- A concept & methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the whole life cycle of a particular product, process, or activity (U.S. EPA, 1993).
- LCA studies analyze the environmental aspects and potential impacts throughout a product's life cycle (e.g., cradle-to-grave) from raw material acquisition through production, use and disposal (ISO).

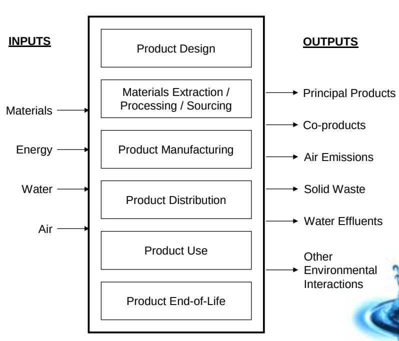


LCA Methodology – ISO 14040



Source: Graedel (2003)

LCA Framework



Source: Adapted from SETAC (1991)

Steps for Life-cycle Analysis

- Problem definition
- Magnitude of the problem
- Scope of assessment
- Functional unit
- Boundary of assessment
- Time horizon of the problem
- Process mapping
- Inputs and outputs of the system
- Fate and transport of pollution
- Impact of pollution on environment
- **Iterative process, not linear!**

LCA Models

- Process-based LCA, developed by SETAC, EPA, & ISO, based on unit process models, process flow diagrams
  - Primary basis for ISO 14000 standards
  - Goal is to include all processes but limited by time or money
- Economic input-output analysis-based LCA (EIO-LCA)
  - Developed by Carnegie Mellon University's Green Design Initiative
  - Boundary is by definition the entire economy, recognizing interrelationships among industrial sectors

Webcast questions?
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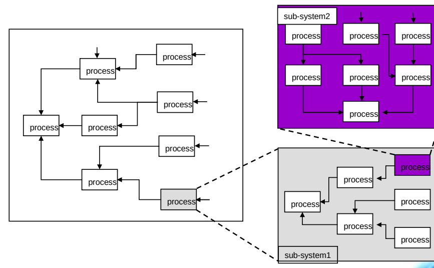
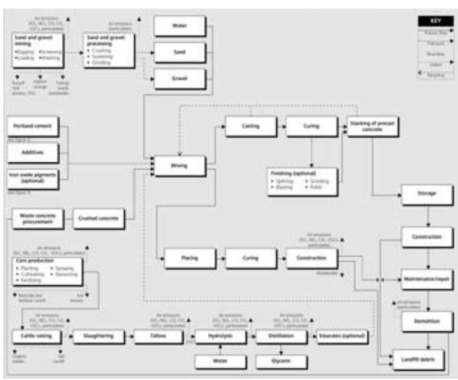
Structure of a Process-based LCA Model

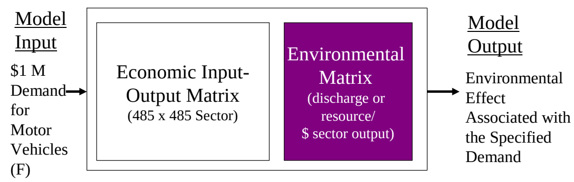


Process Flow of Cement Concrete



AIA, "Environmental Resource Guide," John Wiley & Sons, 1997

Economic Input-Output Analysis-based LCA Model



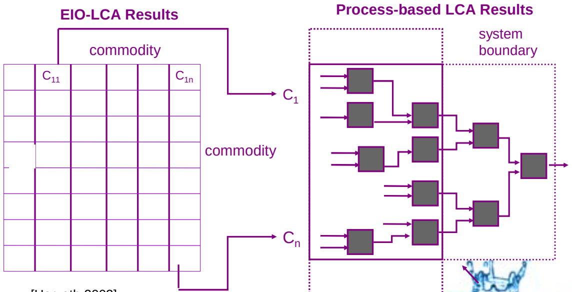
Example of Model Output

	Economic (1992$)	Energy TJ	Iron Ore kg	NOx kg
Total				
Motor Vehicles	x	e		
Steel				

$X = [I - D]^{-1} F$

$E = R X = R[I - D]^{-1} F$

Hybrid LCA



[Horvath 2003]

Impact Assessment

- Global impacts
  - Resource depletion
  - Global warming potential (GWP) in CO_2 equivalents
  - Ozone depletion potential (ODP) in CFC-11 equiv.
- Regional impacts
  - Acidification potential in SO_2 equivalents
  - Land use
  - Water consumption
- Local impacts
  - Human and eco-toxicity
  - Eutrophication
- Other criteria
  - Nuisance (odor, noise, landfill demand, radiation)

Life-cycle Assessment
An Interactive Exercise

Webcast questions or comments?
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Example: Product Shipping

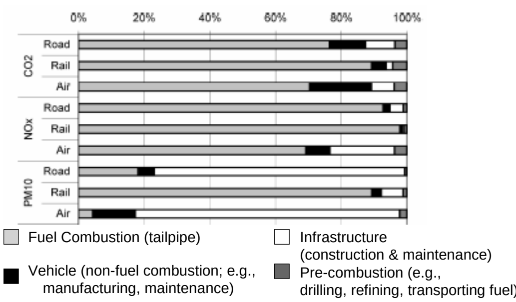
- GHG emissions from delivering 10 lb 1,500 miles by
  - Air: delivered in 2 days
  - Ground: delivered in 5-7 days
- Which alternative is better in terms of environmental performance?
  1. What steps are necessary to complete your life-cycle analysis?
  2. Which questions would you need to ask?
  3. What are the main factors contributing to the environmental performance of both alternatives?

Potential Questions

- Production
  - How is energy used differently in each option?
  - What different materials are used?
- Use
  - How are emissions different for each option?
  - What are maintenance requirements?
  - What is the difference in the service the consumer gets?
- End-of-Life
  - What wastes are produced and what how are they treated?

Shipping Results

	Air Delivery	Ground Delivery
GHG (kg CO_2eq/FU)	10	1.4
NO_x (g/FU)	46	19
PM (g/FU)	6.1	2.6



From Facanha, C., and Horvath, A. (2007). "Evaluation of life-cycle air emission factors of freight transportation." *Environmental Science & Technology*, 41(20), 7138-7144.

LCA: The Pros

- Generally, LCA:
  - Provides new economic and environmental information about products, processes or systems
  - Includes Information about the whole life-cycle, and relationships between life-cycle phases
  - Quantifies impacts of products & processes on flora & fauna
- Companies can:
  - Understand environmental implications of products/processes
  - Identify & minimize sources of pollution & waste
  - Evaluate/benchmark environmental performance
- Can compare alternatives to see how the environmental effects compare

LCA: The Cons

- Lack of comprehensive and reliable data
- Can be expensive and slow
- Defining problem boundaries is controversial and arbitrary.
- No single LCA method is universally accepted.
- Published LCA studies typically document only a few impacts.
- Equally credible analyses can produce qualitatively different results; the results of any particular LCA cannot be defended scientifically.
- LCA cannot capture the dynamics of changing markets and technologies.

LCA Applied to Water and Wastewater

Water/Wastewater Comparisons

- Need to compare
  - equivalent designs where functionality delivers equal benefits
  - life-cycle costs, not just first costs
  - service life/longevity/durability (the role of obsolescence and technological change)
- Valuing environmental burdens depends on risk, perception, and public policy choices

Selected LCA Results for Water Systems

- No-dig pipe installation can decrease CO_2 by 20-30% [Herz and Lipkow 2002]
- Optimal water system steel pipe replacement rate is 50 years [Filion et al 2004]
- RO is the least-environmentally intensive desalination process [Raluy et al 2005]
- Non-potable water reuse treatment processes from least to most emissions: Stabilization pond -> membrane bioreactor -> continuous microfiltration [Tangsubkul et al 2005]
- For WTP, 94% of energy and 90% of GHG in operation phase; 60% of operational burden due to on-site pumping [Racoviceanu et al 2007]

Selected LCA Results for WWTP

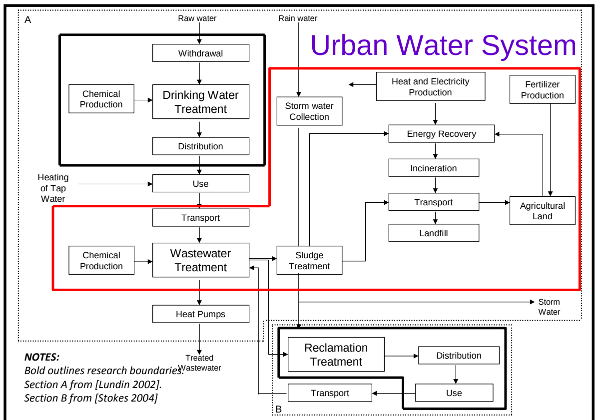
- Anaerobic treatment w/biogas used for electricity/heat is best biogas reuse alternative [Pasqualin et al 2009]
- Anaerobic treatment is most environmentally benign [Murray et al 2008]
- For disinfection, UV has highest environmental costs; energy use and GHGs are lower for anaerobic than aerobic digestion [Beavis and Lundie 2003]
- Combined activated sludge and aerobic digestion has highest GHG emissions [Keller and Hartley 2003]
- WWTPs contribute 41% of energy use & 49% of GHGs in full water cycle [Lundie et al 2004]

Selected LCA Results for Sludge Disposal

- For sludge disposal, best option is combo of land application & use in cement process [Pasqualin et al 2009]
- Sludge incineration is most costly, economically and environmentally [Murray et al 2008]
- Sludge disposal GHGs lowest for cement kiln incineration, highest for landfill & ag spreading [Houillon and Jolliet 2005]
- Agricultural spreading of sludge is environmentally preferable [Palme et al 2005]

WEST/WWEST

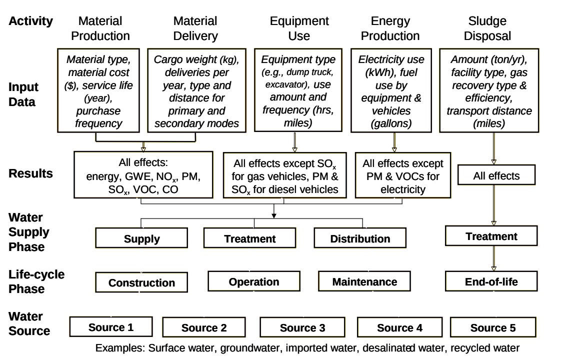
Implementing LCA of Water and Wastewater System



Summary of Components Considered

- Energy consumption
- Material delivery
- Construction processes (e.g., site preparation, earthwork, excavation, and concrete placement)
- Pipes, valves, valve boxes, flowmeters, and fittings
- Pumps and motors
- Electrical and control equipment
- Buildings and structures
- Dams for reservoirs
- Extraction wells
- Chemicals
- Filter media
- Treatment equipment (e.g., flocculation paddles, filters, RO membranes)
- Sludge disposal
- Water tanks

WEST Structure



WEST/WWEST Assumptions

Functional Unit: User-selected in acre-feet (123m liters) for WEST; in MGD or ML/d for WWEST

Analysis Period: Selected by the user

Environmental Effects Considered:

- Energy consumption
- Air Emissions: GHGs (N_2O, CH_4, CO_2), Criteria air pollutants (SO_x, NO_2, PM, CO, Pb), Volatile organic compounds (VOC), select other air emissions
- Global impacts: Global warming effect
- Land emissions
- Water emissions

WEST Input Data Needed

- Material production
  - Pipe length & type
  - Pump number & size
  - Chemical consumption & cost
  - Treatment equipment size & cost
  - Reservoir size & type
  - Building size and type
  - Defaults available, e.g., pipe costs, construction material costs, material service life
  - WWEST has additional defaults
- Material delivery
  - Cargo weight (some defaults)
  - Defaults available for delivery mode and distance
- Equipment use
  - Construction equipment type and hours/miles
  - Fleet & maintenance equipment type and hours/miles
- Energy production
  - Electricity consumption
  - Natural gas consumption
  - Defaults available for electricity mix, vehicle and equipment fuel consumption
- Sludge disposal
  - Sludge volume (defaults in WWEST)
  - Disposal mechanism (e.g., landfill, incineration) and energy recovery details
  - Disposal transport distance and mode

Emission Factor Sources

- Material production Emission factors (EF): EIO-LCA, GaBi
- Material delivery EFs: Facanha 2007 paper, OECD 1997 report
- Equipment use EFs: Chester 2009 paper, CARB off-road emissions model, manufacturers data
- Energy production EFs: EPA's EGRID data, LCA literature (NREL reports, etc.)
- Sludge disposal EFs: EPA's WARM model, LCA literature

Review of WEST and WWEST Data Entry

Limitations of WEST/ WWEST

- In WEST, update data entry methods and provide defaults for system design
- Improve analysis of system equipment inventory and costs, construction process
- Increase impact assessment capabilities
- In the future:
  - Analyze rural/agricultural water applications
  - Include the water use phase (e.g., heating)
  - Add an analysis of the effects of water withdrawal
  - Add assessment of effects of discharging WW effluent, desalination concentrate

WEST/ WWEST Data Quality

	Acquisition method	Data source independence	Representa-tiveness	Data age	Technological correlation
MATERIAL PRODUCTION					
MP defaults (WEST)	NA	NA	NA	NA	NA
MP defaults (WWEST)	3	5	3	2	3
GaBi EFs[1]	4	5	2	3	5
EIO-LCA EFs	3	5	3	2	3
MATERIAL DELIVERY					
MD defaults	3	4	3	5	3
MD EFs	4	5	4	3	4
EQUIPMENT USE					
EU defaults	NA	NA	NA	NA	NA
EU EFs	3	4	3	3	3
ENERGY PRODUCTION					
EP defaults	NA	NA	NA	NA	NA
EP EFs	3	4	4	4	4
SLUDGE DISPOSAL					
SD defaults	NA	NA	NA	NA	NA
SD EFs	3	3	3	3	2

Notes: 5 = Highest; 1 = Lowest; NA = Not available
[1] Plastic pipe, membranes, & certain chemicals (e.g., chlorine, sulfuric acid, alum, ammonia, caustic soda, & polymers)

WEST and WWEST Case Study Results

Webcast questions?
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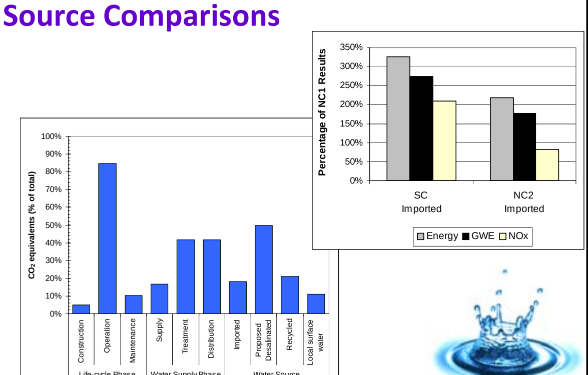
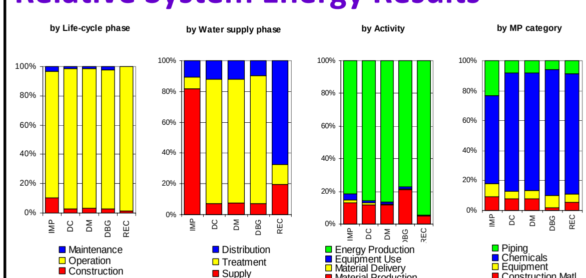
Subject: Question

Source Comparisons



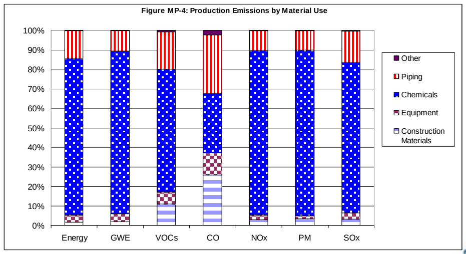
Relative System Energy Results



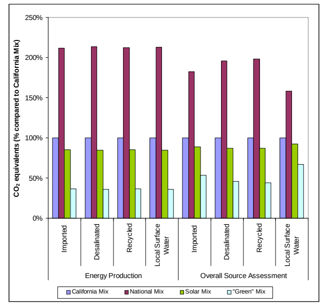
WATER SOURCES: IMP- Imported (CRA/SWP) DC- Desal, conventional pre-treatment DM- Desal, membrane pre-treatment DBG- Desal, brackish groundwater REC- Recycled

Source: Stokes and Horvath, ES&T, 2009

Material Production Results



Desalinated Water with Alternative Energy Sources



	California Mix	National Mix	Solar Mix	"Green" Mix
Ca. Mix	--	--	50%	20%
Coal	1.1	51.7%	0%	0%
Oil	1.4	2.8%	0%	0%
Natural Gas	49.6	15.9%	0%	0%
Nuclear	16.9	19.8%	0%	20%
Other fossil fuels	1.5	0.6%	0%	0%
Hydro	18.8	7.1%	0%	0%
Wind	1.7	20.0%	0%	15%
Solar	0.3	0.0%	50%	20%
Geo-thermal	5.9	0.4%	0%	10%

Sensitivity Results

Result		Sensitive Assumptions
Emissions	Energy	Total water demand (-85%); Electricity generation EF (31%); TP #1 use (-30%)
	GWE	Total water demand (-87%); TP #1 use (-29%); Electricity generation EF (25%)
	NO_x	Total water demand (-90%); TP #1 use (-32%); TP #2 use (-13%)
	PM	Total water demand (-77%); Steel pipe cost (41%); Steel pipe service life (-34%)
	SO_x	Total water demand (-84%); Electricity generation EF (33%); TP #1 use (-29%)
	CO	Total water demand (-81%); Steel pipe cost (33%); TP #1 use (-30%)
Activities GWE	MP	Total water demand (-83%); Steel pipe cost (25%); TP #1 use (-23%)
	MD	Total water demand (-74%); Long-distance truck GWE EF (51%); TP #1 use (-25%)
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Dubai Example

- Population: 2,000,000
- 95% of current water from desalination
- Most electricity from natural gas
- Assuming:
  - 5.6% population growth continues
  - 50% MSF/ 50% RO plant
  - MSF is 24 times more energy intensive and creates 13 times more GHGs [Raluy et al 2005]
- In 2030, desal will consume >136,000 GWh of electricity and emit 21 Tg of GHGs
- Electricity required will be 60% of California's electricity generation

WWEST GHG Results

UNPUBLISHED RESULTS DELETED

TO PROTECT INTELLECTUAL PROPERTY

UNPUBLISHED DATA. DO NOT CITE!

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- One large urban system estimated their GHG emissions as only 35% of the life-cycle results calculated using WEST.
- The supply chain matters!

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  - For imported water, supply phase dominates; for desalination, treatment; for recycled water, distribution.
- For wastewater systems:
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  - Energy recovery is key to reducing environmental effects.

Recommendations

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- Conduct analyses of additional water and wastewater systems to determine what most affects results.
- Encourage utilities to more closely track material and energy use in systems.
- Reassess desalination results as technology improves.
- Encourage supply chain improvements for materials that substantially affect results (chemicals, RO membranes, pipe).

Want to help?

We are looking for help from the industry to:

- Locate a smaller water utility to analyze (serving ~5,000 to 50,000 people)
- Validate default design assumptions in WEST/WWEST
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For more information

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See publications:

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Preferred email for Jennifer Stokes [Draut]:

jrstokes@cal.berkeley.edu or jennstokes@gmail.com

Appendix G.2: Southern California Workshop- LCA for Water & Wastewater Systems: Workshop Slides

Life-cycle Assessment for Water & Wastewater Systems: An Introductory Workshop

Dr. Jennifer Stokes and Prof. Arpad Horvath
Civil and Environmental Engineering
UC Berkeley
OCWD, February 1, 2010

Consortium on Green Design and Manufacturing
University of California, Berkeley

Image from: http://www.idswater.com/

Workshop Outline

- Sustainability:
  - What is it? Why do we care?
  - What can we do about it?
- Introduction to LCA
- Interactive LCA Example
- LCA Applied to Water and Wastewater Utilities
- WEST/WWEST
- Conclusions and Recommendations
- Questions and discussion

Thanks to…

- California Energy Commission Energy Research Grant [CIEE AWARD No. MR-06-08]
- National Science Foundation Graduate Fellowship Program
- University of California Toxic Substances Research and Teaching Fellowship

Sustainability:

What is it and why do we care?

A Grand Vision: Sustainable Development

- Definition: Meeting the needs of the current generation without sacrificing the ability of the future generations to meet their needs. (Brundtland Commission, 1987)
- Myriad alternative processes, materials, designs
  - Examine the environmental implications of each
    - Ask relevant questions and come up with metrics
    - Assess a broad range of environmental effects
  - Need economy-wide, life-cycle perspective
  - Need *progress*, not *growth*

Triple Bottom Line for Sustainability of Infrastructure

- Environmental: natural systems, public health
- Economic: job creation, investments, taxes, public and private services
- Social: safety, equity, civil rights, justice, security, …

What Are The Goals?

- Maintain societal progress while improving environmental quality and quality of life
- Environmental goals
  - reduce non-renewable resource use
  - manage renewable resource use for sustainability
  - reduce toxic substance emissions (heavy metals, solvents, ozone depleting substances)
  - reduce greenhouse gas (GHG) emissions
- Educate the stakeholders
- Do good by doing well
  - profit = revenue - cost

Sustainability: What can we do about it?

First, make sure we understand the problem…

Infrastructure & the Environment

- A total of 2.8 billion Mg of different materials used in the U.S. in 1995 (USGS)
  - 81% by volume were construction materials, mostly stone, sand and gravel
- 25% of virgin wood demand by construction (World Watch Institute, 1995)
- In the U.S., buildings account for
  - 65% of electricity consumption
  - 30% of GHG emissions
  - 30% of raw material use
  - 30% of waste output
  - 12% of potable water consumption
- 12 billion Mg of concrete used annually worldwide
- Apparent flows substantial; non-apparent flows are even larger

Water and the Environment

- Capital spending for water infrastructure is estimated to be $154 - 446 billion between 2000 and 2019 [EPA 2002]
- 2-3% of global energy is used for water and wastewater services; will grow by 33% in next 20 years [ASE 2002]
- One-third of the world lives in nations experiencing water shortages; need 25% more water in the next century to meet global demand [World Bank 2001]
- Eight western states have "substantial" or "high" probability of water shortages by 2025 [USDOI 2003]
- No comprehensive study of the environmental effects of U.S. urban water systems has been conducted…

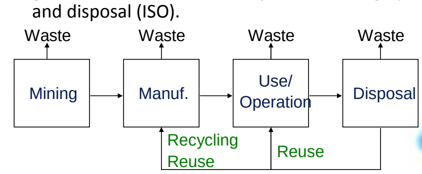
DISCUSSION: What barriers prevent the water industry from doing more to promote sustainability?

Intro to Life-cycle Assessment: An Overview

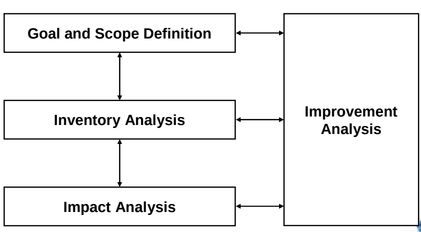
http://cagle.slate.msn.com/news/EnvironmentMadden/3.asp

Life-cycle Assessment (LCA)

- A concept & methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the whole life cycle of a particular product, process, or activity (U.S. EPA, 1993).
- LCA studies analyze the environmental aspects and potential impacts throughout a product's life cycle (e.g., cradle-to-grave) from raw material acquisition through production, use and disposal (ISO).

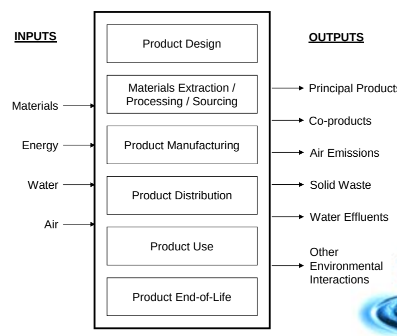


LCA Methodology – ISO 14040



Source: Graedel (2003)

LCA Framework

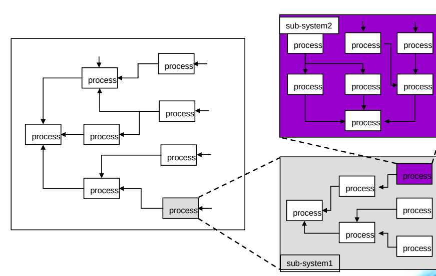


Source: Adapted from SETAC (1991)

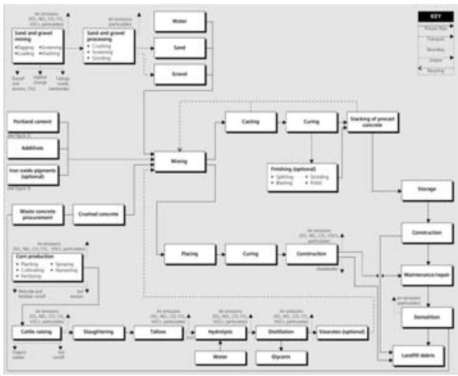
LCA Models

- Process-based LCA, developed by SETAC, EPA, & ISO, based on unit process models, process flow diagrams
  - Primary basis for ISO 14000 standards
  - Goal is to include all processes but limited by time or money
- Economic input-output analysis-based LCA (EIO-LCA)
  - Developed by Carnegie Mellon University's Green Design Initiative
  - Boundary is by definition the entire economy, recognizing interrelationships among industrial sectors

Structure of a Process-based LCA Model

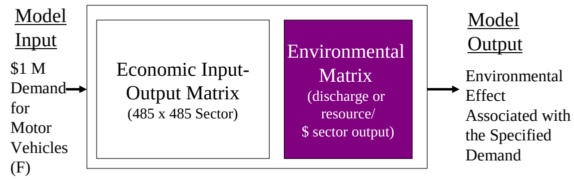


Process Flow of Cement Concrete



AIA, "Environmental Resource Guide," John Wiley & Sons, 1997

Economic Input-Output Analysis-based LCA Model



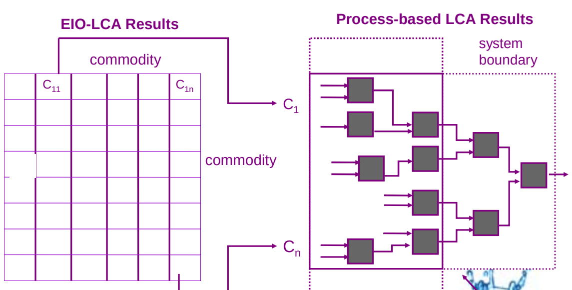
Example of Model Output

	Economic	Energy	Iron Ore	NOx
Total	(1992$)	TJ	kg	kg
Motor Vehicles	x	e		
Steel				

$X = [I - D]^{-1} F$

$E = R X = R[I - D]^{-1} F$

Hybrid LCA



[Horvath 2003]

Impact Assessment

- Global impacts
  - Resource depletion
  - Global warming potential (GWP) in CO_2 equivalents
  - Ozone depletion potential (ODP) in CFC-11 equiv.
- Regional impacts
  - Acidification potential in SO_2 equivalents
  - Land use
  - Water consumption
- Local impacts
  - Human and eco-toxicity
  - Eutrophication
- Other criteria
  - Nuisance (odor, noise, landfill demand, radiation)

Life-cycle Assessment An Interactive Exercise

Example: Wastewater Treatment

- Compare small-scale treatment of raw sewage via
  - Aerated biological filter
  - Reed bed system with septic tank

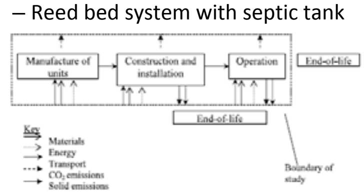


Fig. 1. Boundaries of life cycle study.

Source: Dixon et al 2003, "Assessing the environmental impacts of two options for small-scale wastewater treatment: comparing a reed bed and an aerated biological filter using a life-cycle approach." Ecological Engineering, 20(2003), 297-308.

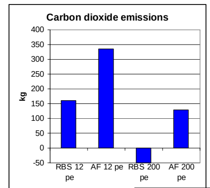
Potential Questions

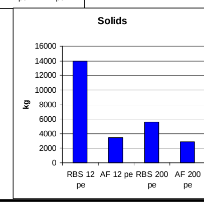
- Which alternative is better in terms of environmental performance?
  - What steps are necessary to complete your life-cycle analysis?
  - Which questions would you need to ask?
  - What are the main factors contributing to the environmental performance of both alternatives?

More specifically,

- Production
  - How is energy used differently in each option?
  - What different materials are used?
- Use
  - How are emissions different for each option?
  - What are maintenance requirements?
  - What is the difference in the service the consumer gets?
- End-of-Life
  - What wastes are produced and what how are they treated?

Results (adapted from Dixon et al 2003)





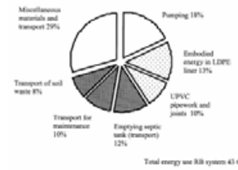


Fig. 2. Life cycle energy utilisation for Reedbed system at 12 p.e.

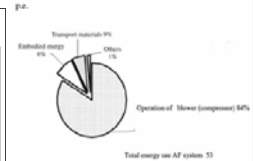


Fig. 3. Life cycle energy utilisation for Aerated filter system at 12 p.e.

LCA: The Pros

- Generally, LCA:
  - Provides new economic and environmental information about products, processes or systems
  - Includes Information about the whole life-cycle, and relationships between life-cycle phases
  - Quantifies impacts of products & processes on flora & fauna
- Companies can:
  - Understand environmental implications of products/processes
  - Identify & minimize sources of pollution & waste
  - Evaluate/benchmark environmental performance
- Can compare alternatives to see how the environmental effects compare

LCA: The Cons

- Lack of comprehensive and reliable data
- Can be expensive and slow
- Defining problem boundaries is controversial and arbitrary.
- No single LCA method is universally accepted.
- Published LCA studies typically document only a few impacts.
- Equally credible analyses can produce qualitatively different results; the results of any particular LCA cannot be defended scientifically.
- LCA cannot capture the dynamics of changing markets and technologies.

LCA Applied to Water and Wastewater

Water/Wastewater Comparisons

- Need to compare
  - equivalent designs where functionality delivers equal benefits
  - life-cycle costs, not just first costs
  - service life/longevity/durability (the role of obsolescence and technological change)
- Valuing environmental burdens depends on risk, perception, and public policy choices

Selected LCA Results for Water Systems

- No-dig pipe installation can decrease CO_2 by 20-30% [Herz and Lipkow 2002]
- Optimal water system steel pipe replacement rate is 50 years [Filion et al 2004]
- RO is the least-environmentally intensive desalination process [Raluy et al 2005]
- Non-potable water reuse treatment processes from least to most emissions: Stabilization pond -> membrane bioreactor -> continuous microfiltration [Tangsubkul et al 2005]
- For WTP, 94% of energy and 90% of GHG in operation phase; 60% of operational burden due to on-site pumping [Racoviceanu et al 2007]

Selected LCA Results for WWTP

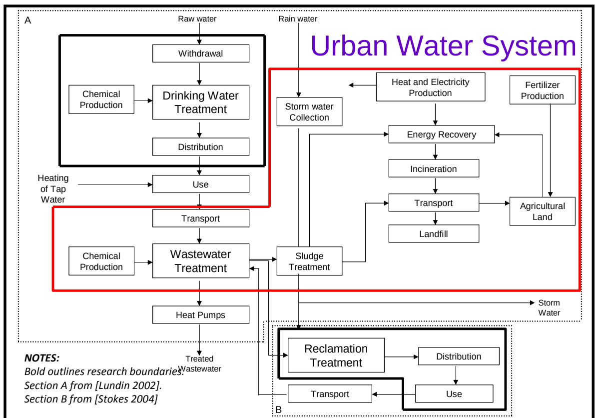
- Anaerobic treatment w/biogas used for electricity/heat is best biogas reuse alternative [Pasqualin et al 2009]
- Anaerobic treatment is most environmentally benign [Murray et al 2008]
- For disinfection, UV has highest environmental costs; energy use and GHGs are lower for anaerobic than aerobic digestion [Beavis and Lundie 2003]
- Combined activated sludge and aerobic digestion has highest GHG emissions [Keller and Hartley 2003]
- WWTPs contribute 41% of energy use & 49% of GHGs in full water cycle [Lundie et al 2004]

Selected LCA Results for Sludge Disposal

- For sludge disposal, best option is combo of land application & use in cement process [Pasqualin et al 2009]
- Sludge incineration is most costly, economically and environmentally [Murray et al 2008]
- Sludge disposal GHGs lowest for cement kiln incineration, highest for landfill & ag spreading [Houillon and Jolliet 2005]
- Agricultural spreading of sludge is environmentally preferable [Palme et al 2005]

WEST/WWEST

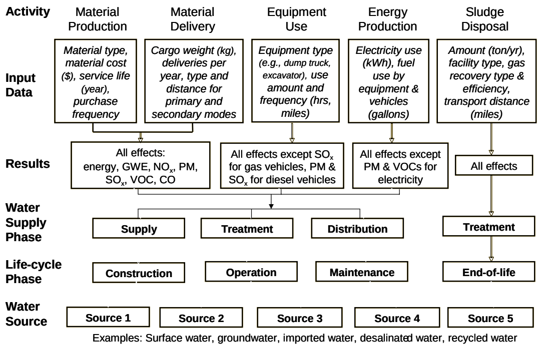
Implementing LCA of Water and Wastewater System



Summary of Components Considered

- Energy consumption
- Material delivery
- Construction processes (e.g., site preparation, earthwork, excavation, and concrete placement)
- Pipes, valves, valve boxes, flowmeters, and fittings
- Pumps and motors
- Electrical and control equipment
- Buildings and structures
- Dams for reservoirs
- Extraction wells
- Chemicals
- Filter media
- Treatment equipment (e.g., flocculation paddles, filters, RO membranes)
- Sludge disposal
- Water tanks

WEST Structure



WEST/WWEST Assumptions

Functional Unit: User-selected in acre-feet (123m liters) for WEST; in MGD or ML/d for WWEST

Analysis Period: Selected by the user

Environmental Effects Considered:

- Energy consumption
- Air Emissions: GHGs (N_2O, CH_4, CO_2), Criteria air pollutants (SO_x, NO_2, PM, CO, Pb), Volatile organic compounds (VOC), select other air emissions
- Global impacts: Global warming effect
- Land emissions
- Water emissions

WEST Input Data Needed

- Material production
  - Pipe length & type
  - Pump number & size
  - Chemical consumption & cost
  - Treatment equipment size & cost
  - Reservoir size & type
  - Building size and type
  - Defaults available, e.g., pipe costs, construction material costs, material service life
  - WWEST has additional defaults
- Material delivery
  - Cargo weight (some defaults)
  - Defaults available for delivery mode and distance
- Equipment use
  - Construction equipment type and hours/miles
  - Fleet & maintenance equipment type and hours/miles
- Energy production
  - Electricity consumption
  - Natural gas consumption
  - Defaults available for electricity mix, vehicle and equipment fuel consumption
- Sludge disposal
  - Sludge volume (defaults in WWEST)
  - Disposal mechanism (e.g., landfill, incineration) and energy recovery details
  - Disposal transport distance and mode

Emission Factor Sources

- Material production Emission factors (EF): EIO-LCA, GaBi
- Material delivery EFs: Facanha 2007 paper, OECD 1997 report
- Equipment use EFs: Chester 2009 paper, CARB off-road emissions model, manufacturers data
- Energy production EFs: EPA's EGRID data, LCA literature (NREL reports, etc.)
- Sludge disposal EFs: EPA's WARM model, LCA literature

Review of WEST and WWEST Data Entry

Limitations of WEST/ WWEST

- In WEST, update data entry methods and provide defaults for system design
- Improve analysis of system equipment inventory and costs, construction process
- Increase impact assessment capabilities
- In the future:
  - Analyze rural/agricultural water applications
  - Include the water use phase (e.g., heating)
  - Add an analysis of the effects of water withdrawal
  - Add assessment of effects of discharging WW effluent, desalination concentrate

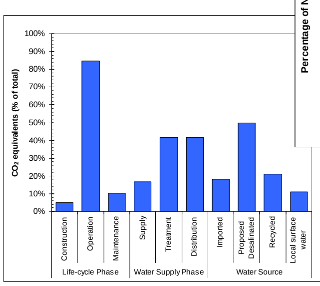
WEST/ WWEST Data Quality

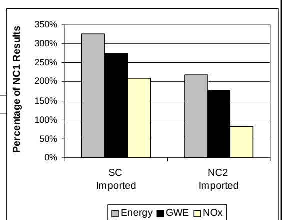
	Acquisition method	Data source independence	Representa-tiveness	Data age	Technological correlation
MATERIAL PRODUCTION					
MP defaults (WEST)	NA	NA	NA	NA	NA
MP defaults (WWEST)	3	5	3	2	3
GaBi EFs[1]	4	5	2	3	5
EIO-LCA EFs	3	5	3	2	3
MATERIAL DELIVERY					
MD defaults	3	4	3	5	3
MD EFs	4	5	4	3	4
EQUIPMENT USE					
EU defaults	NA	NA	NA	NA	NA
EU EFs	3	4	3	3	3
ENERGY PRODUCTION					
EP defaults	NA	NA	NA	NA	NA
EP EFs	3	4	4	4	4
SLUDGE DISPOSAL					
SD defaults	NA	NA	NA	NA	NA
SD EFs	3	3	3	3	2

Notes: 5 = Highest; 1 = Lowest; NA = Not available
[1] Plastic pipe, membranes, & certain chemicals (e.g., chlorine, sulfuric acid, alum, ammonia, caustic soda, & polymers)

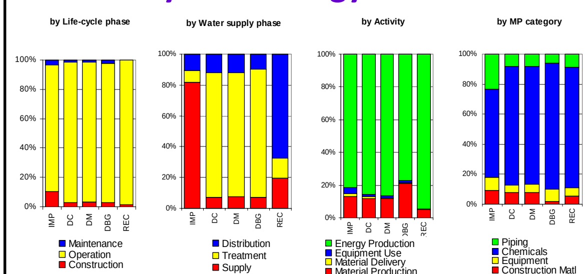
WEST and WWEST Case Study Results

Source Comparisons





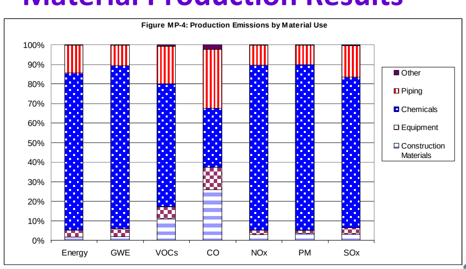
Relative System Energy Results



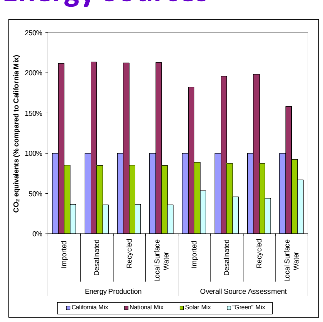
WATER SOURCES: IMP- Imported (CRA/SWP) DC- Desal, conventional pre-treatment DM- Desal, membrane pre-treatment DBG- Desal, brackish groundwater REC- Recycled

Source: Stokes and Horvath, ES&T, 2009

Material Production Results



Desalinated Water with Alternative Energy Sources



	California Mix	National Mix	Solar Mix	"Green" Mix
Ca. Mix	--	--	50%	20%
Coal	1.1	51.7%	0%	0%
Oil	1.4	2.8%	0%	0%
Natural Gas	49.6	15.9%	0%	0%
Nuclear	16.9	19.8%	0%	20%
Other fossil fuels	1.5	0.6%	0%	0%
Hydro	18.8	7.1%	0%	0%
Wind	1.7	20.0%	0%	15%
Solar	0.3	0.0%	50%	20%
Geo-thermal	5.9	0.4%	0%	10%

Sensitivity Results

Result		Sensitive Assumptions
Emissions	**Energy**	Total water demand (-85%); Electricity generation EF (31%); TP #1 use (-30%)
	GWE	Total water demand (-87%); TP #1 use (-29%); Electricity generation EF (25%)
	NO_x	Total water demand (-90%); TP #1 use (-32%); TP #2 use (-13%)
	PM	Total water demand (-77%); Steel pipe cost (41%); Steel pipe service life (-34%)
	SO_x	Total water demand (-84%); Electricity generation EF (33%); TP #1 use (-29%)
	CO	Total water demand (-81%); Steel pipe cost (33%); TP #1 use (-30%)
Activities GWE	**MP**	Total water demand (-83%); Steel pipe cost (25%); TP #1 use (-23%)
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Preferred email for Jennifer Stokes [Draut]:

jrstokes@cal.berkeley.edu or

jennstokes@gmail.com

Appendix H: Task 10

Appendix H.1: General Study Assumptions H-2

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Appendix H.1:
General Study Assumptions

The following default assumptions are included in WWEST. The user is able to edit many of these assumptions, if desired.

For system buildings:

- Unless more specific information was available, reinforced concrete buildings were assumed to have a 2 to 3 foot (ft.) thick foundation and 1-ft. thick walls. Wastewater treatment process system components were assigned average thicknesses based on the overall depth and material. Tanks/basins/reactors can be either steel or concrete, generally concrete is assumed to be the default except chemical storage. These assumptions can be edited by the user. Reinforced concrete is assumed to contain 2% steel by volume.
- Lift station size was assumed to be a function of the number of pumps housed within the facility. Lift stations are assumed to have an area of 150 square feet (ft^2) per pump. Lift stations are, by default, assumed to be partially buried. The user can define the dimensions for each facility and determine whether the station is above or below ground. An "average" (partially buried) option is also available when conditions vary for multiple stations within a category.
- Electrical and control system components at all facilities, as well as piping and landscaping at treatment plants, were not specifically inventoried. Electrical and control equipment are assumed to be valued at 3% and 9% of equipment costs in the given system, respectively (Peters 2003). Piping within treatment plants (e.g., chemical delivery systems) and landscaping were similarly estimated as 17% and 2.5% of equipment costs, based on the same source. Piping within treatment systems was assumed to be composed of polyvinyl chloride (PVC) pipe and metal valves.

For wastewater pipelines:

- Pipe lengths were grouped into broad categories based on diameter and material for simplicity. The diameters to define each category depended on the application (e.g., discharge pipe ranges cover larger diameter pipe; treatment plant pipe, smaller; collection pipe is most diverse and has the most and broadest ranges). Pipes were consolidated into five common materials: (1) concrete, (2) vitrified clay (VCP), (3) Iron and steel (4) PVC, and (5) other plastics. Pipe size and cost information is included in Appendix B.7.
- Fittings (e.g., bends, wyes, tees, reducers) were assumed to be located on average every 250 ft. in the collection system and every 500 ft. in the discharge system. The user can define a different interval. For estimating purposes, all fittings were assumed to be ductile iron 90° bends. Fitting size and cost information is included in Appendix B.7.
- Isolation valves are assumed to be placed every mile of pipe in the collection and discharge systems if the user does not enter specific valve information. Costs were

available for butterfly, gate, check, and globe valves (Means 1997, Peters 2003). The average cost for all valves types of a particular diameter was used in the calculations. Valve size and cost information is included in Appendix B.7.

For construction processes:

- Construction and equipment use effects were assessed based on what it would take to construct the system under modern conditions. The results do not reflect the actual emissions from construction, because much of the infrastructure is several decades old. Technology and emission standards have changed since construction took place.
- Equipment use impacts are included for a cement mix truck, dump truck, loader, excavator, compactor (plate and roller models), crane, concrete pump, and concrete vibrator are incorporated automatically into the assessment. Other equipment will be used during construction, including welding equipment, booms, generators, and air compressors. The user can enter additional equipment use information for all equipment and can enter information for custom equipment not previously included in WWEST.
- Emission factors depend on the equipment model year and, for diesel road equipment, the cumulative number of miles traveled by the truck. The cumulative miles factor accounts for increasing emissions as the equipment ages. All equipment was assumed to be from the 2006-2007 model year; diesel trucks were assumed to have 40,000 cumulative miles.
- Soil compaction was assumed to be done in 6-in. lifts. For all excavation activities (e.g., buried pipelines, valve boxes, and foundations), the area was excavated 2 ft. deeper and an average of 4 ft. wider than required for the facility and the soil beneath the foundation was compacted. It was assumed that soil volume would increase by 133% when excavated and decrease to the original volume when re-compacted.
- Excavations for pipelines were assumed to be 2 ft. deeper and 1.5 to 2 times diameter wider than the pipe. The pipe depth can be defined by the user depending on pipe diameter; default pipe depths are 4-6 ft.
- Reinforced concrete used in construction was assumed to be composed on 2% reinforcing steel by volume. The actual proportion of reinforcing steel depends on the engineering design and will vary. Plywood forms were assumed to be used for cast-in-place concrete. These forms are assumed to be used three times prior to disposal.
- Assumptions about hours of equipment use were based on industry norms (Means 1997) and manufacturer's data for specific models. These values assume that earthwork is done in common soil. Emissions will increase if conditions are more unfavorable. The user can edit emission factors to account for more complicated work environments, if desired.

For material delivery:

- The default transportation mode used to deliver system components was determined based on the transport distance. If the transport distance was 50 miles or less, a local truck was assumed to be used. For distances between 50 and 1,500 miles, a long-distance truck was assumed to be used. When the transport distance exceeded 1,500 miles, the equipment was assumed to be transported primarily by rail. When rail was used, it was assumed that secondary transport by local truck was necessary for the final 30 miles. Transport distances and modes can all be edited by the user.
- One exception to the material delivery assessment is concrete delivery. Because concrete must be delivered in special concrete mixer trucks, the emissions due to concrete delivery are included in equipment use rather than material delivery.
- Material delivery calculations require material mass. The mass of certain components mass was not available and could not be estimated. This is especially true for materials in highly aggregated categories where the mass of materials included varies widely, including landscaping, electrical equipment, and control equipment. A gross estimate of 0.15 kg per dollar value was used to estimate weight for electrical and control equipment. As a result, material delivery emissions are underestimated. However, the effect associated with delivery of these materials is expected to be negligible. In the future, a method for estimating the mass of these materials will be sought.

This section is a representative, but not a comprehensive, listing of all assumptions included in the WWEST calculations. Other assumptions are described and documented within the tool.

Appendix H.2:
Case Study Details

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 several different communities. The utility has a single wastewater treatment plant (WWTP), described in Chapter 11 of the text. The collection and discharge infrastructure are detailed below..

Collection Infrastructure Summary

The utility collects sewage from several contiguous communities. Each of these communities operates independent sewer systems which collect sewage from residences and businesses. The utility owns and operates infrastructure which collects sewage from these systems and transports it to the treatment plant. Only infrastructure owned and operated by the utility is included in the analysis. Table 1 summarizes the length and material of pipe included in the collection system.

Table 1: Collection Pipe Summary

Pipe Material	> 36 in dia.	15 - 36 in dia.	< 15 in dia.
Steel		42,800	3,900
Concrete	130,000	23,000	
Vitrified Clay		3,100	

All pipe greater than 36 inches in diameter is analyzed as 60-inch diameter pipe. For the 15 to 36-inch range, the diameter is assumed to be 24 inches. Pipe in the smallest diameter range is assumed to be 12-inch diameter pipe.

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 Table 2.

Table 2: Lift Station Summary

Building Area Range (sf)	Facilities (#)	Pumps (#)
< 750	7	1.5 hp (2); 3 hp (4); 15 hp (4); 60 hp (4)
750 - 1500	4	5 hp (3); 10 hp (1); 30 hp (2); 70 hp (2); 200 hp (2)
> 1500	4	15 hp (3); 70 hp (3); 77 hp (2); 160 hp (4); 200 hp (3)

The utility did not provide and inventory of fittings and valves included in the collection system. We assumed there was a fitting for every 100 feet of pipe and five valves four each of the lift stations.

Discharge Infrastructure Summary

The utility discharges liquid effluent to an outfall in the San Francisco Bay. The discharge piping includes 108-inch pipe on land. Wastewater is discharged through a 48- to 96-inch diffuser about 5,700 feet offshore. Table 3 summarizes the length and material of pipe included in the utility's discharge pipeline.

Table 3: Discharge Pipe Summary

Pipe Material	<100 in dia.	>100 in dia.
Steel		
Concrete	6,300	9,200
Vitrified Clay		

All pipe greater than 100 inches in diameter is analyzed as 108-inch diameter pipe. For smaller pipe, the diameter is assumed to be 96 inches. No pump stations are present because the effluent flows by gravity. No fittings or valves were included in the analysis due to lack of data.