Carbon and Water Resource Management for Water Distribution Systems

By

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Abstract

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Water distribution systems (WDS) worldwide face increasing challenges as population growth strains a limited water supply in many areas. In the United States, existing water infrastructure systems require significant investments to refurbish an aging stock of assets. Much of this investment is required in drinking water transmission and distribution, where a substantial amount of material and economic inputs are lost as a result of pipeline leaks. With growing worldwide concern for reducing environmental impacts of the built environment, infrastructure investment on the scale of WDSs must be accurately assessed for potential unintended consequences. U.S. water infrastructure systems have already been identified as a major consumer of energy: it is estimated that 13% of the total U.S. electricity demand is consumed by water-related energy use.

The existing literature on environmental assessment of WDSs does not provide a comprehensive, detailed picture of the total impacts of utilities. The current body of knowledge either omits common WDS elements or focuses on solving theoretical design problems. This research provides a framework for the most comprehensive greenhouse-gas (GHG) emission assessment of U.S. WDSs with the most accurate data available. This research presents opportunities for incorporating environmental metrics into asset management, a popular management strategy used by utility managers worldwide. The major contributors to emissions in WDSs are identified, and cost-effective solutions for reducing GHG emissions are recommended. A major opportunity in cost-effective GHG reduction lies in effectively reducing distribution losses from leaks in pipelines. This dissertation provides a model, tool, and analysis solutions that help communicate the GHG emissions associated with leaks and the related economic costs for reducing these leaks.

This dissertation employs life-cycle assessment (LCA) in determining the GHG footprint of a WDS. LCA is a commonly used, holistic environmental assessment method. Products and processes are analyzed from "cradle to grave" which implies that all supply chain entities, both upstream and downstream, are

included in the assessment. This research uses hybrid LCA methods to reduce uncertainty in providing the most accurate assessment possible.

The study focuses on four major elements of a WDS: water storage, pipes, water wells, and pumping. These entities, namely water storage, water wells, and booster pumps, have never been analyzed at this level of detail in previous research. Each element is separately analyzed for GHG contributions to a drinking water utility's footprint. Whenever possible, the most relevant LCA data are used in creating the overall model. This represents a WDS LCA with better data than have previously been used in any of the existing literature, which often omits infrastructure aspects or reuses inaccurate data from previous work.

The scope of work includes material production, construction, operation, and maintenance of a case study U.S. WDS. Material production includes all supply chain entities involved in delivering materials for use in the WDS. Construction involves all equipment use and temporary materials used in the assembly and installation of the WDS elements. Operation and maintenance encompasses all emissions that result from inputs related to the delivery of drinking water to customers after construction is completed. Determining the GHG emissions of leaks in distribution and transmission is a major facet of the operation and maintenance assessment. A tool is developed to calculate pipe replacement scheduling based on GHG emissions from leaks.

The LCA results are based on a case study for a distribution system utility located in the Western United States. The case study utility draws all water from a large, pristine aquifer and pumps this water to storage tanks at higher elevations to create a gravity fed system. It has no dedicated transmission lines, and the high pressure spikes from pumping with a small operating budget have created a WDS that loses 40% of pumped and treated water in distribution.

The LCA results show that pumping energy contributes the majority to the case study utility's GHG footprint, accounting for 84% of the total emissions. Losses, the majority of which are assumed to be leaks by the case study utility, contribute 40% to this number. Piping materials (6%) and maintenance (5%) are the next largest contributors to the total GHG emissions for a 50-year analysis period. Projections for growth show that decarbonization of the local electricity mix and reducing distribution losses could significantly reduce GHG emissions despite service growth for the case study utility. Assessing water storage options showed that concrete reservoirs had significantly higher impacts than steel tanks on a storage capacity basis.

As distribution losses from leaks were found to contribute significantly to the GHG footprint, this research developed a "breakeven" tool to give utilities an environmental perspective on pipe replacement scheduling. The tool's results show that accrued GHG emissions quickly matched the emissions that would result from construction and material inputs from replacing the pipe, even for modest leak increase rates. These results are in stark contrast to the case study utility's current replacement schedule, which operates on a 300-year cycle due to economic constraints.

To give the breakeven tool results more context, this dissertation uses the utility's reported pipe replacement costs to compare GHG emissions and economic costs for different leak scenarios. This comparison effectively allows utility representatives to visualize the costs of potential GHG emission savings by reducing leaks. For the case study utility's inputs, avoiding GHG emissions through pipe replacement was revealed to be cost effective.

Although the case study utility has unique aspects uncommon to many U.S. WDSs, such as the high loss volume and low treatment inputs, the LCA model assesses other materials and processes that can be applied to GHG assessments of other WDSs. The new LCA data sources reduce uncertainty for future applications. This research provides evidence that WDSs can cost-effectively reduce their GHG footprint, and that the entirety of WDS infrastructure can be targeted for GHG reductions by policy makers.

The GHG intensities of drinking water and cost effectiveness of GHG savings through leak reduction were estimated for California and Texas. These scenario analyses showed that values vary with different regions based on the treatment and pumping requirements, and that there are diminishing returns for GHG savings in leak reduction. Still, the economic cost of avoiding emissions through leak reduction was determined to be an extremely cost-effective option for carbon abatement when compared to other infrastructure solutions, such as renewable energy options.

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Glossary of Terms

AM	Asset Management
ASCE	American Society of Civil Engineers
AWWARF	American Water Works Association Research Foundation
BAU	Business as usual
CAC	Carbon Abatement Cost
DI	Ductile iron (piping)
DICL	Ductile iron concrete lined (piping)
EBMUD	East Bay Municipal Utility District
EIO-LCA	Economic input-output-based life-cycle assessment
EPA	U.S. Environmental Protection Agency
GA	Genetic algorithm
GDP	Gross domestic product
GHG	Greenhouse-gas
GIS	Geographic information system
GWP	Global warming potential
HDD	Horizontal direction drilling
HDPE	High-density polyethylene
LCA	Life-cycle assessment
LCEA	Life-cycle energy assessment
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
MG	Million gallons
NERC	North American Electric Reliability Corporation
PE	Polyethylene
PVC	Polyvinyl chloride
SETAC	Society of Environmental Toxicology and Chemistry
WDS	Water Distribution System
WEST	Water-energy Sustainability Tool
WWEST	Wastewater-energy Sustainability Tool

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In the time since obtaining my undergraduate degree from Carnegie Mellon, no one has been more helpful in my professional development than my friend and graduate advisor, Professor Arpad Horvath. He has welcomed me to UC Berkeley's exceptional civil engineering program not once but twice, the latter coming when I was struggling to find direction and confidence in my career. He has challenged me to seek a level of achievement and quality of work that I had never imagined possible. More than anything he has made this process enjoyable from start to finish, where I have found a value in my everyday work that I had never obtained before.

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And Mary Katica, who has both tolerated and supported me at every step, I am endlessly thankful to have by my side.

1. Introduction

1.1 Introduction

Water distribution systems (WDS) worldwide face increasing challenges as population growth strains a limited water supply in many areas. These infrastructure systems, which account for the supply and treatment of drinking water from source to final consumption, must be expanded or changed to meet the growing demand. It's estimated that 25-30% of water is lost in distribution in WDSs worldwide, costing $14 billion annually.[1] Facilities must be upgraded to reduce inefficiencies, such as leaks, to protect and extend current resources before consuming new resources, such as desalinated ocean and brackish water, that will require greater energy inputs to make suitable drinking water.

In the United States, drinking water demand continues to increase while the aging of the existing supply infrastructure requires substantial attention. In 2009 the EPA projected a needed investment of $335 billion over 20 years to U.S. drinking water systems, as shown in Figure 1.[2] The majority of this investment is needed in infrastructure systems for distribution of drinking water, where water losses due to pipeline degradation have become common. The ASCE gave these drinking water systems a grade of D, where 7 billion gallons of water are lost daily in leaks.[3,4]

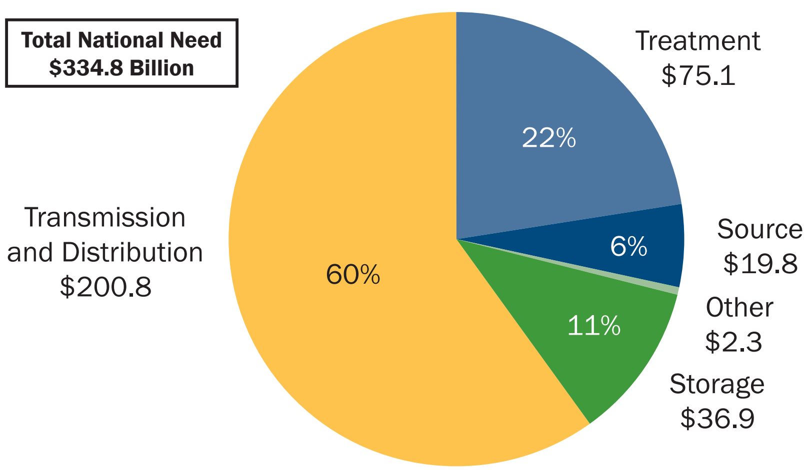

Figure 1. Allocation of investment needs for U.S. WDSs in billions of 2007 U.S. dollars. Source: (2).

Most in need of these infrastructure investments are the arid regions of the United States, where much of the economy is based on a high volume of water supply, and where several states face extreme water scarcity problems.[5] One of these states, Texas, is currently experiencing one of the worst droughts in its history. At the end of 2011, 67% of the state was in "extreme" or exceptional drought, and agricultural production losses had cost the state's industry $5.2 billion.[6] This number is compounded by the expectation that water demand will rise 22% by 2060 while groundwater resources are being depleted much faster than they can be recharged. In response, voters have approved major investments into state WDSs to alleviate the crisis.

Any complex infrastructure investment on this scale will create major environmental impacts. Massive material production, construction efforts, and new treatment needs will require significant energy and resource inputs. Water-related infrastructure systems are already major consumers of energy. One report estimates that water and wastewater services consume 3% of U.S. electricity consumption and 7% of global energy consumption, with total global water and wastewater infrastructure energy consumption expected to grow by 33% over the next 20 years.[7] Another report estimates all water-related energy use as 13% of the total U.S. electricity demand.[8] The California State Water Project is the greatest consumer of energy in the state, utilizing 2-3% of the state's total electricity in moving water from northern sources to southern users.[9] These environmental considerations must be quantified accurately and communicated properly before the sizeable investments are committed to a final course of action.

1.2 Distribution Water Losses

Significant environmental impacts from WDSs lie in water losses in distribution and transmission. In the example of Texas, losses are currently at 13% (of total volume distributed) statewide.[10] In other major U.S. cities losses can be as large as 30%.[11] In most cases, the majority of these losses come from leaks due to structural problems in pipelines. If these losses from leaks could be reduced, major environmental savings could be accomplished nationwide.

Water that is lost in distribution and transmission can occur for multiple reasons, and it is important that the different types of losses are defined. Table 1 displays the different sources of losses.

<table>
<tr><td rowspan="4">Distribution Water Losses</td><td rowspan="3">Apparent Losses</td><td>Unauthorized consumption: theft of distributed water.</td></tr>
<tr><td>Inaccuracies in metering at service connection.</td></tr>
<tr><td>Systemic data errors: errors that arise from transmission of data from metering point to reporting of consumption data.</td></tr>
<tr><td>Real Losses</td><td>Leakage in distribution: water lost from leaks and breaks throughout the distribution system from source to customer meter.</td></tr>
</table>

Table 1. Definition of distribution water losses. Adapted from (12).

In this dissertation, whenever statistics are given for losses in distribution, both apparent and real losses are included. Distribution losses also imply any losses experienced in transmission of water from water source to final consumption. The leak reduction implications detailed in this research focus on reducing real losses. Real losses are usually the largest contributor of losses for WDSs experiencing large volumes of losses (greater than 50%).[11] Some portions of real losses are assumed to be unavoidable. These losses are small leaks that occur at valves or pipe connections, and are referred to as background leaks.[13] However, breaks that occur within distribution mains are controllable and contribute significantly to real losses. These leaks are the focal point for the greenhouse-gas (GHG) emission reduction options discussed later in the text.

2. Research Goals and Scope

2.1 Problem Statement

Decision-makers, composed of utility representatives, regulators, and policy makers, should be fully aware of potential opportunities for environmental impact reduction in the placement of new facilities and refurbishment of existing systems. To achieve this, these industry players must have access to complete and thorough environmental assessments that use the most accurate information available. The results of these assessments must be effectively communicated to utilities, where solutions for impact reduction opportunities can be identified. The current body of knowledge does not sufficiently meet these needs.

The existing literature in environmental assessment of WDSs does not provide a comprehensive, detailed picture of the total impacts of a utility. The results of existing studies are not assessed by every contributing WDS element. Certain elements, such as water storage, are based on very general data, or are omitted entirely. Assessment methods are limited, and the same data sources are reused in the literature. Distribution losses from leaks have only been loosely explored, and current work does not provide context for how they can dynamically contribute to a utility's environmental footprint. Other environmental assessment studies of WDSs are focused on theoretical design problems and are not geared to aid utility decision-makers in reducing their footprint. These oversights and failings of the current body of literature have left the WDSs without proper knowledge to both quantify and reduce their environmental impacts.

2.2 Objectives

This research closes the existing knowledge gaps by applying comprehensive environmental assessment techniques and the best available data to all aspects of a WDS. This dissertation creates tools and methods for utilities to expose every savings opportunities cost effectively. These tools and methods are also designed and communicated in such a manner that they can be immediately relevant and useful to decision-makers.

The objectives of this dissertation are to accurately detail the GHG footprint of a U.S. WDS, and provide currently attainable solutions for WDSs to cost-effectively reduce their carbon footprint. To accomplish this, the following questions are answered:

- What are the biggest contributors to GHG emissions in components common to U.S. WDSs, and how can these emissions be effectively reduced?

- How do leaks in drinking water distribution systems impact the overall GHG footprint of a utility? How can these impacts be reduced, and what are the associated economic costs?

• How can we better understand how decisions are made by drinking water utilities to effectively communicate cost-effective opportunities for reducing GHG emissions?

This dissertation research uses life-cycle assessment (LCA) to quantify the GHG emissions. The complete emissions are detailed by each contributing infrastructure element, and are based on the most accurate data available. Several of the specific elements are further analyzed to incorporate not only an environmental perspective, but also economic and asset performance. These perspectives are included to allow utilities to better incorporate the findings of this research into managerial decision-making.

2.3 Research Scope Definition

Employing comprehensive environmental assessment methods demands that all supply chain processes are included in the study's scope. This approach is applied to every possible element of a U.S. WDS.

Figure 2 shows the scope of this research. It includes all supply chain elements of a WDS except end of life, which was not considered due to lack of data. It was unclear how the majority of WDS elements were disposed of because of the long associated service lives. Elements that are decommissioned simply stop being used but are left in place, such as underground pipes that no longer serviced customers.

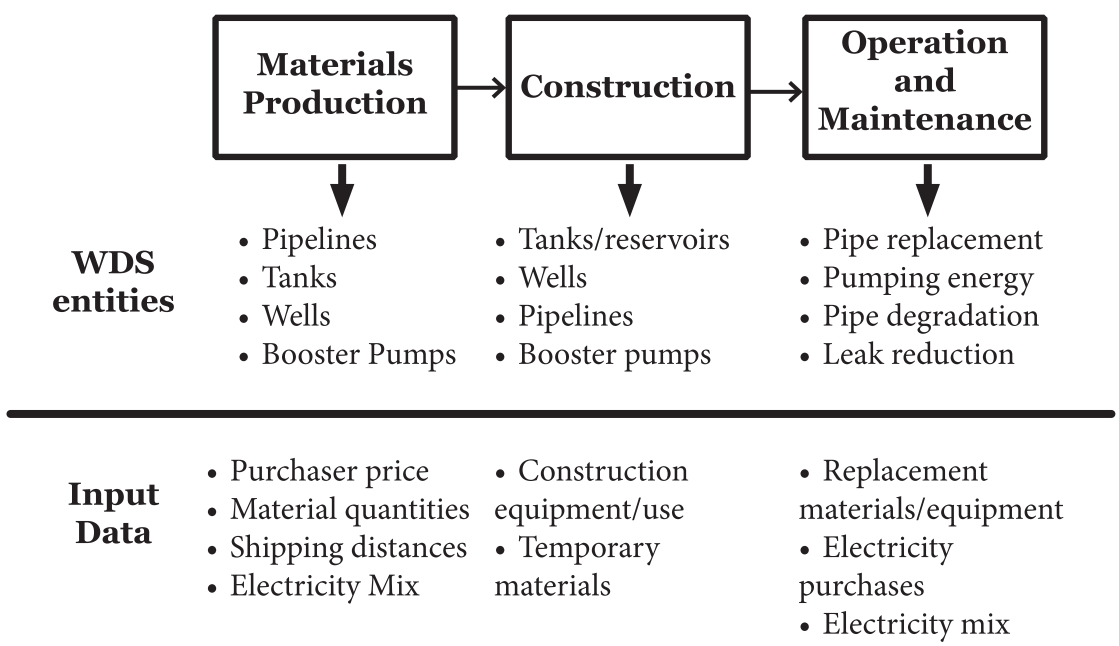

Figure 2. Scope of the study.

The remaining scope yields an inclusive assessment of a case study U.S. WDS. Materials production incorporates all upstream supply chain entities to the point of construction. This includes geographical considerations such as electricity mixes and shipping distances. Construction is composed of all emissions related to the assembly and installation of WDS infrastructure elements. This includes on-site equipment use and temporary materials. Operation and maintenance encompasses all emissions that result from inputs related to the delivery of drinking water to customers after construction is completed. Some materials or inputs are continually used in this phase, such as treatment chemicals, electricity for pumping, and repair/replacement of pipelines.

The final sum of the outputs from the assessment creates a GHG footprint for a case study utility that has provided data to the research. The major contributors to the total GHG footprint are further detailed to give more insights to the results.

To better understand leaks, a major contributor to the case study utility's GHG footprint, the results are used to develop a "breakeven" tool that analyzes an isolated length of piping to better understand the impacts of leaks and provide utilities with a method for viewing pipe replacement from an environmental perspective.

The tool results (GHG outputs and pipe replacement rate) are quantified for economic costs as well. A multiobjective optimization problem is created by determining acceptable leak rate options that seek to minimize both GHG emissions and economic costs in pipe replacement scheduling. Leak reduction is given further context by determining the potential costs for avoiding a large quantity of GHG emissions.

The potential policy implications and barriers to achieving GHG reductions in U.S. WDSs are discussed in the final chapters of this dissertation. The data sources used are qualitatively assessed for the associated uncertainties.

This research provides a guide for U.S. WDSs to accurately assess their GHG footprint by tracking the entire lifetime of the infrastructure system. New infrastructure elements are analyzed to fill existing gaps in the current body of WDS environmental assessment research. Cost-effective solutions are determined for the greatest contributors to total GHG emissions within the case study utility, providing results that can be customized to other U.S. WDSs seeking to reduce GHG emissions.

2.4 Asset Management as a Context for Research

This research fits in a wider context that seeks to create environmental solutions for water infrastructure systems aligned with the utility management technique of asset management (AM). Fully detailed in Chapter 3, AM seeks to promote efficiency and minimize waste at every level of a complex infrastructure system, but does not traditionally have an environmental focus. Figure 3 displays a summary of environmental solutions that fit within the scope of asset management for water and wastewater infrastructure systems.

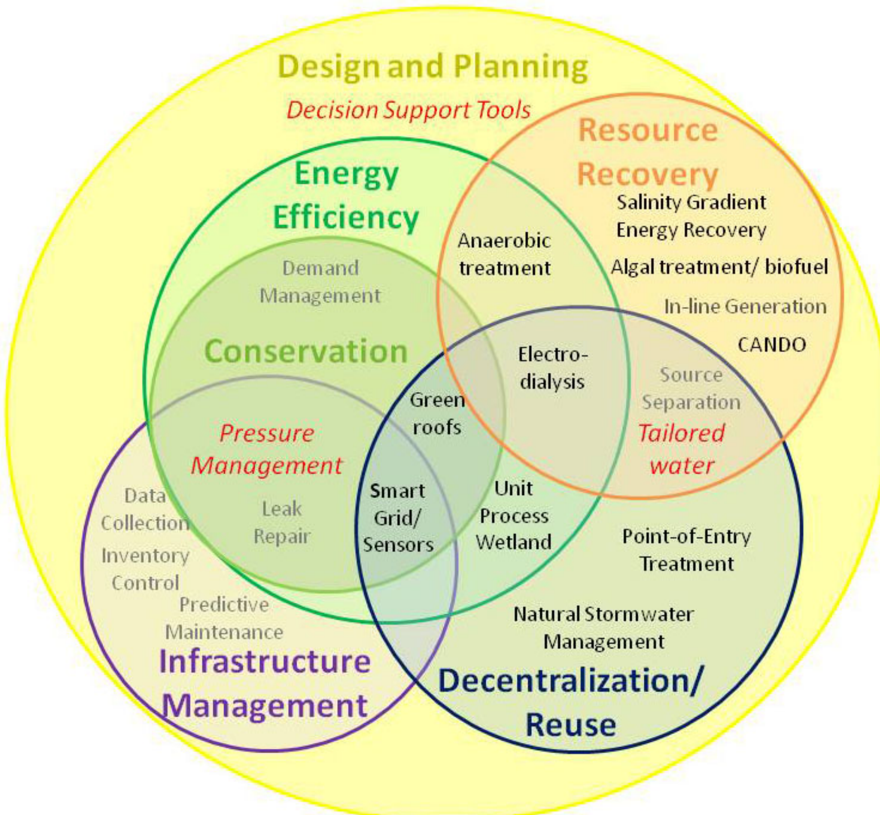

Figure 3. Broad scope of research topics for sustainable water infrastructure systems. Source: (14).

Environmental impacts, namely those associated with emissions of GHGs and criteria pollutants, will soon need to become an integral part of a utility's evaluation of the true cost of delivered drinking water. By determining comprehensive environmental impacts for WDSs with large asset bases, this research inherently aligns with AM goals of full-cost accounting.

In the context of Figure 3, this dissertation research falls best in the broad research themes of infrastructure management, conservation, and energy efficiency sectors. Specifically, predictive maintenance, inventory control, and leak repair are essential themes of this research. This dissertation is most closely related to other AM environmental research topics such as water conservation, pressure maintenance, and data collection, all of which are directly related to the major topics of this research. These research relationships are discussed more fully in connection with the final results in Chapter 8.

Other research topics displayed in Figure 3 are indirectly connected; they are not actively discussed in this dissertation and are not included in the scope of the model and results. This includes research areas such as resource recovery or decentralization/reuse. For example, a topic such as natural stormwater management will be affected by a WDS's management decision to reduce distribution leaks, which will reduce total flows that potentially discharge into the external environment. However, leak reduction is not a primary concern for designers of natural stormwater management facilities.

3. Approach and Methodology

3.1 Asset Management

Asset management can be defined as an infrastructure management concept that seeks to cost-effectively maximize the performance of each system element (asset). The technique is useful for utilities as they are often forced to manage massive asset bases with strict financial constraints. AM concepts initially began to be practiced in drinking water utilities in the United Kingdom when the industry was privatized. AM envelopes many focuses, from accurate data collection to lean management, but the core values remain the same:[15]

- AM is a business driven approach. A utility's success is measured by business performance indicators (e.g., profit).
- AM approaches management with a life-cycle perspective; assets must be managed throughout the whole product/process lifetime.
- AM strives to achieve the greatest cost efficiency and risk reduction while providing the target service level.
- AM encompasses many disciplines, beyond engineering, in properly managing complex systems.

Much of AM is directed at obtaining accurate information and understanding the best ways to apply it. This approach is essential for WDSs for addressing issues such as consumption metering and pipeline maintenance. Errors in metering are commonplace and can let major losses in distribution go unnoticed.[13] Determining the quality of underground asset, such as piping, is very difficult, and is compounded by the fact that many miles of piping are necessary in urban WDSs. The most important aspect for effective AM, when applied to vast infrastructure systems such as these, is to create a culture that promotes AM at every level of the utility, so that even the lowest level decision makers play an active role in maintaining the culture.[16] This type of culture allows data to be collected at every possible opportunity, which can then be used at the highest levels of the utility management.

The work presented in this dissertation has close ties to AM for WDSs. As environmental impacts become a greater point of emphasis for policy makers, utilities will need to incorporate mitigation into all aspects of their operations. LCA is a powerful tool for accurately exposing the greatest contributors to impacts, and the method presented in this work can be recreated for drinking water utilities with similar common assets. This work also details how this LCA method can be tied to managing individual pipe assets, determining when optimal replacement should be performed from both environmental and economical perspectives. This dissertation also delves into leaks and pipe degradation, currently one of the most critical AM topics for WDSs.[13]

3.2 Life-cycle Assessment

This research employs LCA in quantifying the environmental impacts of a WDS. Formal LCA emerged in the 1990s as a form of environmental analysis for products and processes to more accurately assess direct and indirect contributions to impacts. The methodology arose from a widely-identified need for comprehensive analysis of environmental problems. In LCA, products and processes are assessed from "cradle to grave", creating a holistic method of analyzing the entire life cycle.[17] Figure 4 shows the major life-cycle stages, inputs, and outputs in LCA evaluations.

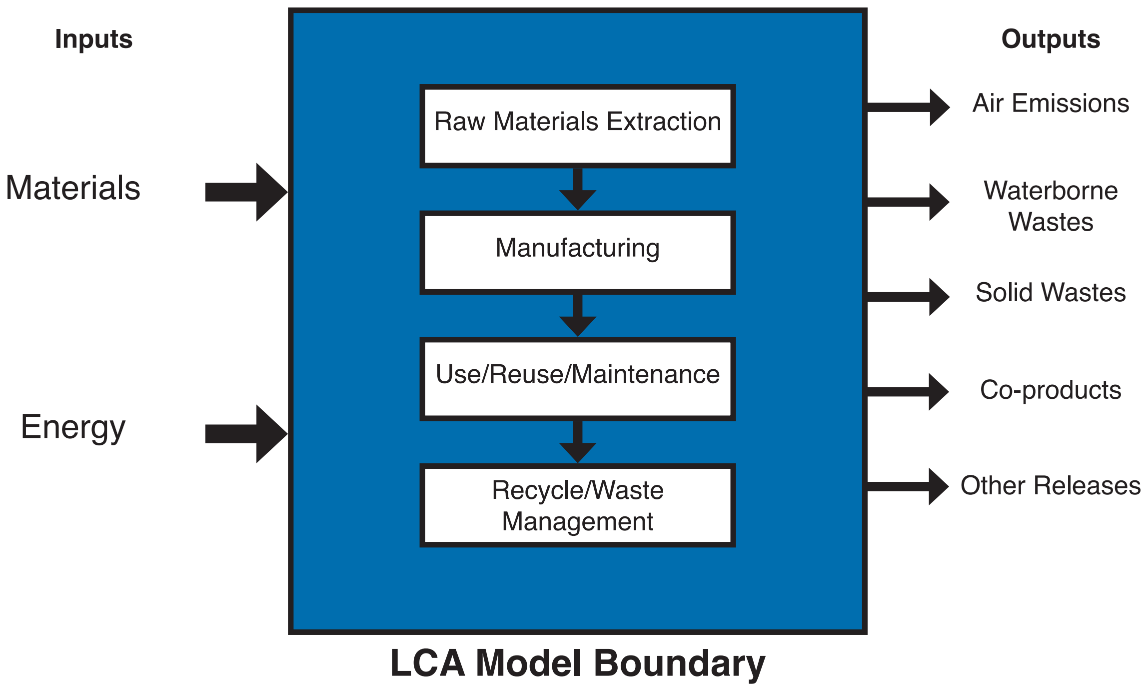

Figure 4. A basic LCA structure. Adapted from (17).

While many environmental footprint studies may only focus on one phase of a product's lifetime, such as assessing a WDS for only pumping energy and treatment, this approach could omit several aspects that could contribute significantly to the overall environmental impacts. A complex supply chain involving hundreds of different materials, such as piping mains or water tank materials, must be produced to create the final product. Raw materials must be extracted, refined, and shipped before parts can be produced and assembled. These processes represent the upstream supply chain of a WDS in operation, and must be assessed to create a proper environmental profile of the final product. However, for a full "cradle to grave" assessment, the WDS must be analyzed for its post-operation life-cycle phases. Certain materials will be recycled or reused, while others will be landfilled. These processes will require separate energy and material inputs and should be included in the assessment if possible. A complete LCA creates a full, detailed picture of where the greatest environmental impacts occur in a product's lifetime, and where the best opportunities exist to reduce these impacts.

To achieve a complete LCA, difficulties lie in obtaining comprehensive and high-quality data. Without comprehensive data, scopes will be limited and potential impacts will be lost in the analysis. LCAs must also account for spatial and temporal specifications. In the final stages of an LCA, calculating certain impact categories can be difficult with high levels of uncertainty.

LCAs are completed using two methods: Process-based assessments and Economic Input-output based analysis (EIO-LCA).

3.3 Process Life-cycle Assessment

The process-based method is the original and more traditional method of performing an LCA. This method was developed in the mid-90s primarily by the U.S. Environmental Protection Agency (EPA) and the Society for Environmental Toxicology and Chemistry (SETAC).[18]

Process-based LCA is performed in four primary steps:[19]

- Goal and Scope Definition - Outlining the purposes of the study and defining the boundary of the work. It is important to understand what is feasible based on the resources available in this stage. A strong definition allows for repeating the study and objective evaluation. Stating the functional unit for the LCA also occurs in this stage.

- Life-cycle Inventory Analysis (LCI) - Quantifying the impacts at each stage of the life cycle through data collection and calculations. Impacts are usually tracked in the form of emissions and consumption (energy, water). All quantities are based on the predefined functional unit for the different stages.

- Life-cycle Impact Assessment (LCIA) - Selecting, classifying, and characterizing the results from LCI. LCI results can be converted into environmental indicators, but it is difficult to fully detail how these indicators become final impacts (endpoints).

- Interpretation and Analysis: The LCI and LCIA Stages are summarized. Conclusions and recommendations are created for decision-making based on the original goals stated for the LCA.

The basic methodology allows for a well-controlled, detailed analysis. Researchers can be very specific about the product they assess and what metrics should be tracked. For a complex product, such as an automobile, a process-based study can become incredibly detailed as each impact must be calculated for each individual stage. Studies are often hampered by a lack of data, time, and money. To manage the constraints, project scopes become more confined and streamlined. As a result, many supply chain aspects are excluded when using this method.

The most important aspect in avoiding these drawbacks of process-based methods is to properly define the scope of the study at the outset. This can avoid lost time researching areas that have low-quality data or high levels of uncertainty. If it is found that certain aspects of the initial scope will prove too uncertain later in the research work, the scope should be amended to exclude these aspects before time and effort are lost.

3.4 Economic Input-output-based Life-cycle Assessment

Economic Input-output-based LCA (EIO-LCA) takes a much different approach than process LCA to create a very comprehensive method that is faster and less costly. In the 1930s, economist Wassily Leontif developed economic input-output analysis as a means of modeling the interactions between U.S. industries. The model uses linear algebra to determine what direct and indirect economic inputs contribute to produce different products. Table 2 displays the variables used in an economic input-ouput model.

Output From Sectors (i)	Input to Sectors (j)				Intermediate Outputs (O_i)	Final Demand (F_i)	Total Outputs (X_i)
	1	2	3	n			
1	X_{11}	X_{12}	X_{13}	X_{1n}	O_1	F_1	X_1
2	X_{21}	X_{22}	X_{23}	X_{2n}	O_2	F_2	X_2
3	X_{31}	X_{32}	X_{33}	X_{3n}	O_3	F_3	X_3
n	X_{n1}	X_{n2}	X_{n3}	X_{nn}	O_n	F_n	X_n
Intermediate Inputs (I_i)	I_1	I_2	I_3	I_n			
Value Added (V_i)	V_1	V_2	V_3	V_n		GDP	
Total Inputs (X_i)	X_1	X_2	X_3	X_n			

Table 2. Economic input-output model. Source: (18).

An intermediate output (O_i) represent the sum of a single sector's output across all other sectors. This intermediate output is then the total economic interactions between this sector and all others. The total output (X_i), equivalent to the total input, is the sum of these interactions and the final demand supplied to the customer. The gross domestic product (GDP) is the total of these final demands. This can be mathematically sated as:

$$X_i = \sum X_{ij} + F_i$$

where X_{ij} represents sector i's output into sector j. These sector interactions can be normalized to a per dollar basis to create direct requirement (D_{ij}) factors for each interaction:

$$D_{ij} = \frac{X_{ij}}{X_j}$$

The total output can now be stated as:

$$X_i = \sum D_{ij} X_j + F_i$$

This is displayed in matrix format as:

$$X = DX + F$$

Where X represents the total output vector, D the direct requirements matrix, and F the final demand vector. This can be rearranged as:

$$X = (I - D)^{-1}F = TF$$

Where I represents the identity matrix and T the total requirements matrix. The term $(I - D)^{-1}$ is also called the Leontief inverse. This term denotes an infinite series composed of the economy's supply chain contributing to the final output.

Researchers at Carnegie Mellon University applied environmental metrics to this methodology to determine the environmental impacts associated with economic outputs of products. This interaction is accomplished by attaching environmental impact factors to each of the direct requirements:

$$b_i = R_i TF$$

where b_i represents the environmental burdens and R_i is a matrix representing the environmental impacts per dollar of output for each sector interaction[17].

This approach creates a very comprehensive and rapid assessment of common products and processes where all industry interactions included in the 400+ sectors are involved in the final assessment. However, the method contains associated uncertainties in its sources and calculations. The method uses aggregate data, so specific products cannot be distinguished, and uses U.S. averages which often do not reflect local details. This approach poses problems when assessing products that are imported, or when attempting to differentiate between two similar products (such as water pumps). Using only U.S. averages can create inaccuracies as well. For example, concrete produced in Ohio will have very different environmental outputs than concrete from California, as Ohio has a much more coal intensive electricity mix.

3.5 Hybrid Methods

Both methods possess advantages and uncertainties. Combining both methods in a single study constitutes the Hybrid method. In a hybrid approach, the researcher incorporates the most appropriate LCA method at each stage to expand the system boundary as much as possible while providing the most accurate results.[20] While uncertainties will continue to exist in any LCA, employing hybrid methods reduces these uncertainties when the method for assessment is carefully considered at each stage.

3.6 Environmental Indicators

LCA allows the opportunity to quantify several environmental metrics associated with a product or process. This research specifically focuses on GHGs. GHGs, for this study, are tracked through carbon dioxide equivalents ($CO_{2(eq)}$) for a 100-year time scale, also called global warming potential (GWP). This approach signifies that any air emissions that contribute to greenhouse effect, or global warming, are normalized to a common metric. The GWP is calculated for a GHG as follows:

$$GWP = \frac{\int_0^T \Delta f_g \times R_g(t)dt}{\int_0^T \Delta f_{CO_2} \times R_{CO_2}(t)dt}$$

where f represents the radiative forcing and R represents the persistence (mass of gas remaining after T years). In this research, T is 100 years. The three most common GHGs contributing to GWP in this research are CO_2, methane (CH4), and nitrous oxide (N_2O). Table 3 displays the 100-year GWP of each of these GHGs (IPCC 2007).

	GWP ($CO_{2(eq)}$)		
GHG	**20-yr**	**100-yr**	**500-yr**
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153

Table 3: GWP for common GHGs. Source: (21).

Table 3 only displays GWP for the most common GHGs. Other chemicals, such as hydrofluorocarbons and ethers, can contribute significantly to GWP. This research, however, tracks only CO_2, CH_4, and N_2O.

GHG emissions are the chosen metric for this study because of the strong connections to policy implications and the limitations of the scope of the study. Existing data that quantify environmental impacts of typical WDS elements, namely pipes, are limited to GHG emissions and energy consumption of production. Although it would be possible to create other environmental metrics from energy consumption, such as air-pollutant emissions (nitrous oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), particulate matter (PM), volatile organic compounds (VOCs), ozone (O_3)), it is unclear for much of these data what types of fuels are used (primary or secondary energy) and how they are combusted. Making assumptions for these inputs and production methods would create strong uncertainties in the final results, which would undermine the potential benefits that the models could provide when limiting the scope.

4. Related Literature

4.1 Asset Management Literature

Asset management, as described previously, can be a vital tool for the utility's ability to identify the best practices for achieving efficiency in managing its wide array of infrastructure elements. Effective AM relies on obtaining accurate data for each asset and involving decision makers at every level of the utility. For WDSs, obtaining accurate data for assets is essential in accurately determining accurate distribution losses and reducing these losses through proper maintenance scheduling. The two studies described below explore both the general hurdles of applying AM and the technical details needed to apply methods to individual assets.

Ugarelli et al. 2010 outlined a method for applying asset management principles, identified as managing physical assets of an infrastructure system efficiently through the life-cycle, to wastewater systems. Collecting accurate data and properly applying them are determined to be the most important facets in the study. The difficulties of these challenges in applying AM are discussed within the context of a case study: a wastewater system in Oslo, Norway. The study observed Oslo's increased maintenance and expansion in the wastewater system between 1991-2006. Using full-cost accounting with AM, the authors calculated an expenditure projection for 2000-2015, and discussed the greatest hurdles the system planners would need to overcome in this period. In this case, data collection and proper application are identified as the greatest challenges.[22]

AWWARF 2007 identified the most cost-effective leakage management practices worldwide and applied them to four North American case studies of water distribution utilities in El Dorado, CA, Seattle, WA, Halifax, CAN, and Philadelphia, PA. In each of the of the utilities, 4 methods of leak reduction (in chronological order) were implemented:

- Conducting a standardized water audit: a detailed water audit to determine the level of distribution losses and weak points in the data collection quality.
- Establishing district-metered areas: designated areas within the WDS are closely monitored for inflow and outflow to accurately determine the level of losses for that area.
- Implementing pressure management: high pressure spikes can create structural leaks in pipes and also increase background leakage, contributing significantly to water losses in distribution.
- Applying new technologies: using new leak detection technologies to actively locate leaks with better tools.

The study found that district metered areas and pressure management were the most successful tools for reducing water losses. Similar to Ugarelli et al. (2010), the study found that data management (through district metered areas) was key.[22,13]

4.2 Life-cycle Assessment of Water Distribution Systems

Because WDSs are such large, life-supporting infrastructure systems, previous research has applied LCA techniques to analyze these systems. However many of these studies focus only on certain portions of a WDS, or exclude significant supply chain aspects. Geographical considerations and local conditions also represent an integral part of WDS LCAs, which will vary in any utility studied. Past LCAs have detailed many different aspects of WDSs:

- Pipelines – existing work has detailed several different common piping materials and applied them to WDS applications.
- Pumping energy – using Bernoulli's equation, pumping energy demands for WDSs have been modeled. Some studies go in great detail to determine the theoretical pumping energy demand at any given point in a WDS.
- Pipe degradation – previous, non-LCA work has generally modeled how pipes can degrade over time in different conditions. This work has been incorporated into LCAs to determine environmental impacts over a given time frame.
- Pipe maintenance – pipe replacement and maintenance have been incorporated into WDS LCAs by predicting breaks, or creating a set pipe replacement schedule.

The studies below represent the available studies that apply LCA methods to WDSs and related systems.

Lundin and Morrison 2002 created a framework for assessing the sustainability of water and wastewater utilities using environmental sustainability indicators and LCA. The LCA scope included water withdrawals, treatment and distribution of drinking water, collection and treatment of wastewater, and wastewater by-product management (sludge, biogas, heat). The framework was applied to two case studies in Goteberg, Sweden and King William's Town, South Africa. These case studies were given letter grades (Goteberg a B, and King William's Town a D). The study provided LCA sources for certain elements common to WDSs, but the wide scope and selective sustainability indicators (mainly based on water use and quality) leave several data gaps.[23]

Rihon et al. 2002 used SimaPro Eco-Indicator 99 to quantify LCA impacts of the water and wastewater system of the hydrographic basin of "La Vesdre" in Belgium. The study's scope included drinking water distribution and treatment, and wastewater transmission and treatment. Losses were stated to be included in the scope but are not disseminated in the results. Pumping energy (33%) and wastewater treatment (17%) contributed the most to the global environmental impacts. Purification (drinking water treatment), and water supply each contributed 13% to the total impacts. The study presented a wide variety of results (ecoscore, human health impacts, resource use, eco-system quality), but no details were provided for inputs to the SimaPro model.[24]

Filion et al. 2004 performed a life-cycle energy analysis (LCEA) for a water distribution system. The study's scope included material production, operation and maintenance, and end of life. Materials were limited to pipelines, which were found by using the "steel pipes" sector in EIO-LCA. Maintenance was calculated in the study by predicting break rates and including materials necessary to replace a standard break length. Pumping energy inputs included frictional losses over time. This framework was applied to the New York, NY water supply tunnel system for a 100-year analysis period, where a 50-year replacement time for pipes was found to be optimal to reduce materials for breaks and head losses from friction. The study contributed to WDS LCA by providing details for assessing pumping energy, head losses, and pipe materials, but still left out many infrastructure entities and did not disseminate results by different stages/elements.[25]

Lundie et al. 2004 performed an LCA of the Sydney, Australia water distribution and wastewater systems. The study included outputs for 7 different impact categories. The study's scope included drinking water distribution and filtration, wastewater transmission and sewage treatment. Distribution pumping and sewage treatment were found to contribute the most to climate change outputs. Infrastructure materials were included, but construction inputs were not. The study also included results for different projections in changes to electricity mix, service population, efficiency upgrades, and different water sources (desalination). Desalination and sewage treatment upgrades were found to significantly increase energy demand and outputs to climate change.[26]

Stokes and Horvath 2006 developed the Water-Energy Sustainability Tool (WEST) for evaluating water source options in California using hybrid LCA methods. WEST is presented in great detail later in this chapter. Desalination proved to have 2-18 times more emissions from high-energy inputs than importation or recycling of water. Each of the three options had different life-cycle stages dominating the environmental impacts. This study presented the first and most complete, publicly available WDS LCA to date, but still contained omissions of infrastructure elements that are detailed later in this chapter.[27]

Arpke and Hutzler 2006 performed an LCA for domestic water consumption to compare the impacts of water use, electricity generation, and energy consumption for water treatment and domestic water heating. The study's scope included drinking water transmission, distribution, treatment, domestic energy inputs, and wastewater treatment. Results were disseminated by energy requirements for drinking water treatment and distribution (0.11-0.66 kWh/m^3), domestic water heating (6.3-36 kWh/m^3) and wastewater treatment (0.21-0.66 kWh/m^3). The study did not include material inputs for elements other than chemicals in treatment, and only includes direct energy inputs (electricity for pumping, fuel for heating) beyond these treatment materials.[28]

Landu and Brent 2007 developed a process-based LCA of a water supply system for an industrial zone in South Africa. The scope of this study included material production, treatment of drinking water, transmission to an industrial zone. Only chemicals for treatment were considered in material production. The LCI inputs were based on 2002 data. LCIA was included in the study where 5 different resource-use impact categories were determined and analyzed. Results included characterization factors for the drinking water supply system. The study concluded that water use impacts were the most significant based on total water use, water scarcity, and excess water use. Twenty percent losses in distribution contributed to the impacts. The study developed valuable results for the case study region but still leaves out many WDS elements that can contribute to impacts.[29]

Friedrich et al. 2009 performed an LCA for a drinking water system in Durban, South Africa. Three options were analyzed for increasing service to 200,000 new customers (functional unit): maximizing use of existing infrastructure, water recycling, and creating new infrastructure. The study's scope included material production, drinking water treatment, transmission, and wastewater treatment. Material production included a dam and piping system. Water losses (20-30%) were included in distribution impacts for maximizing existing infrastructure and constructing new infrastructure options. Implementing recycling was found to have the lowest impacts (CO_2 emissions), but a blend of the three options was recommended to utilities seeking to reduce their emissions. A simple bottled water delivery scenario was also analyzed, which had much higher emissions than the three options. The study found that 75% of the impacts for bottled water were attributed to producing and distributing the bottle materials. The study created an example by which different supply alternatives could be evaluated with LCA, but lacked detail for utilities to recreate the analysis.[30]

Stokes and Horvath 2009 evaluated different desalination techniques including seawater and brackish groundwater, along with imported and recycled water. This study used WEST to evaluate the four different water sources for use in California. The study's scope included material production, drinking water treatment, and transmission of treated water to urban water centers. The desalination techniques were evaluated using different energy mixes consisting of a sample U.S. mix, international mixes, and a photovoltaic mix. Results found that desalination of ocean water had the greatest associated environmental impacts (energy use, GHGs, nitrogen oxides (NO_x), sulfur oxides (SO_X), particulate matter (PM)), and if California switched entirely to desalination drinking water treatment processes would consume over 50% of the state's total electricity use. This study expanded on the authors' 2006 work to include new water sources that had yet to be assessed, but still omitted several WDS elements. These omissions are further discussed later in the chapter in a more detailed assessment of WEST.[31]

Mo et al. 2010 created an input-output LCA of a water distribution system and applied it as a case study to a water and wastewater system in Kalamazoo, MI. The study included 424 commodity sectors in its analysis that were aggregated into "water, sewerage, and other systems", which is a reflection of the operation and maintenance of a water and wastewater utility and "non-residential systems", which encompasses all construction inputs into a utility. This study used utility economic cost data to create a system for predicting the total annual energy demand of the system. While water movement (pumping) dominated the results, non-movement inputs accounted for 34% of the final energy demand. While this study presented a highly comprehensive input-output model that was specific to the case study's region, the different contributing elements cannot be distinguished based on the results that are only disseminated by direct and indirect energy inputs.[32]

Stokes and Horvath 2011 applied WEST to a Northern California water and wastewater utility that serves over 1 million people. The study's scope is the same as the authors' previous studies (Stokes and Horvath 2006, 2009), but introduced construction, equipment use, maintenance, and sludge disposal to the WEST tool. Both probabilistic and deterministic results were detailed. The results were disseminated in greater detail than the authors' previous work that included elements such as specific piping materials (steel and ductile iron pipe). However, all pipes were assessed using EIO-LCA, which can be inaccurate for specific materials as discussed in Chapter 3. Energy inputs had the greatest impacts, but material production for chemical treatment was also significant. This study represents the most recent published results using the WEST tool, which is further analyzed later in this chapter.[33]

Borghi et al. 2013 performed an LCA of the WDS system servicing Sicily, Italy. The study's scope included drinking water treatment, transmission, and distribution. The LCI inputs were based on 2009-2010 data. The study found that desalination efforts, which only provided 13% of the total water delivered, accounted for 74% of the total GHGs emitted by the WDS. Eleven different environmental impact categories were analyzed including energy use, material use, water consumption, and waste production. The study recommended desalination treatment should be reduced in the water supply to reduce energy consumption and impacts. The study presented a detailed assessment of a case study's treatment and electricity use, but omitted material production and cannot be easily adapted to other similar utilities.[34]

4.3 Design Problems

Some WDS environmental assessments studies are analyzed as design problems and do not strictly adhere to LCA methodologies. The case studies assessed range from simple, theoretical systems to more complex, real systems. These design problems optimize system designs through single or multiobjective methods. The most common case in multiobjective optimization is to design for both environmental performance and economic costs. In the literature reviewed, only two studies utilize LCA methods and are the minority among these design problem studies.

Many of these design studies utilize genetic algorithms (GAs) to identify a set of optimal solutions. GAs are derived from the same principles that drive natural selection and evolution. A GA draws from a population of "chromosomes" and selects combinations of these chromosomes that have a better chance of creating solutions than those that do not. GAs are typically used for non-linear problems: problems where variables cannot be solved for independently.[35] This method is thus attractive to WDS design problems that seek to optimize multiple objectives such as economic costs and environmental impacts. Designing even a simplified WDS depends on several infrastructure elements (storage, pipelines, pumps, elevations) that will vary when seeking to minimize certain objectives (pumping energy, materials, maintenance) while still maintaining necessary criteria (consumption flow, pressure).

Many of these design problem studies employ Pareto efficiency to give more context to multiobjective problem solutions. This evaluation technique isolates a set of ideal alternatives when given several options to optimize multiple criteria.[36] These optimal solutions create a Pareto frontier, which identifies the only efficient solutions available in a multiobjective optimization problem.

Dandy et al. 2008 analyzed a two-reservoir theoretical case study that had been used in previous WDS optimization studies. The study determined a Pareto frontier when optimizing for economic costs and embodied energy per meter of pipe length for two types of polyvinyl chloride (PVC) piping. The embodied energy of the pipe product included raw materials extraction to operation, although no pumping energy was considered as the system was designed to be gravity fed from reservoirs at higher elevations.[36]

Herstein et al. 2009 analyzed a small, theoretical WDS using EIO-LCA. The WDS design included a single source, one pumping station, a storage reservoir, and connecting pipelines. The study used a multiobjective optimization model for minimizing costs and environmental impacts. Economic costs and environmental impacts were based on required pumping energy and piping materials. The impacts for 20 different environmental metrics were combined by a weighting method to give each alternative a single environmental performance score. For most environmental metrics pumping energy dominated the total impacts. The study created 25 options for WDS design scenarios, but only one optimal design alternative was identified.[37]

Wu et al. 2010a used a modified GA in a WDS design problem for minimizing economic costs and GHGs. The case study was a theoretical WDS that delivered water to a small town from two storage tanks through booster pumps. Total economic costs consisted of capital costs (pipes and pump stations), pump replacement costs, and operational costs (electricity pumping demands). Emissions were characterized by capital (pipes) and operational (electricity) emissions. Discount rates were varied for both GHGs and costs that created several Pareto frontiers in which carbon abatement costs were identified. Capital investments dominated costs, while operational actions dominated GHG emissions over 18 different design solutions.[38]

Wu et al. 2010b compared multiobjective and single-objective optimization solutions for two simple case studies in WDS design. Both case studies were theoretical with different levels of complexity. The first case study included a water source at a lower elevation, a pump and pipeline connecting to a storage tank at a higher elevation. The second case study is similar to the first, but included 3 storage tanks at the same elevation, increasing the pipe network and number of nodes. The design objectives for the multiobjective optimization, based on a GA, were to minimize economic and GHG costs, where GHGs were monetized using carbon pricing. The single-objective problem combined the two into a single cost. Emissions and economic costs were largely the same as Wu et al. 2010a, with diurnal demands and pipe roughness being included. Both case studies revealed the same trends when comparing the single and multiobjective optimization problems. The multiobjective model was concluded to have more computational complexity, and provided decision-makers with more information in determining potential solutions with a Pareto frontier.[39]

Herstein et al. 2011 quantified economic costs and multiple environmental impacts for expansion options for a theoretical WDS that was adding a water storage tank. The original WDS included a pumping station, 2 water tanks, and pipe network that included several nodes. Environmental impacts were found using the EIO-LCA model. The study's scope included material production (water tanks and pipes), and water distribution. All pipeline maintenance was assumed to be replacement. Pumping energy included pipe degradation for increased head losses. The multiobjective optimization was performed using a GA. Pareto frontiers were created for two optimization problems: minimizing pumping energy and capital costs, minimizing pumping energy and environmental impact index. The environmental impact index was created by combining 14 different environmental indicators based on EIO-LCA model results. The study found that the environmental index was inversely related to capital costs, whereas the index and pumping energy were linearly related since environmental impacts were dominated by pumping energy demand. The study introduced environmental assessment techniques for new WDS elements in steel water tanks. However, the impacts were not related to any specific design but a general, estimated cost that was applied to a loosely related EIO-LCA sector ("water, sewer, and pipeline construction"). The environmental index quantified in this study has an extremely high degree of uncertainty as combining such a wide array of different impacts, which were already calculated with the associated uncertainty of EIO-LCA, into a single score and cannot accurately reflect how these impacts are valued by different audiences.[40]

Wu et al. 2012a developed a pumping power estimation calculation to compare variable-speed pumps and the traditionally used fixed-speed pumps in water transmission. This pumping power calculation was incorporated into a GA to create a multiobjective optimization problem in the design of a case study adapted from Wu et al. 2010b. The design was optimized for minimizing economic costs and GHG emissions. The study found that incorporating variable-speed pumps in design created savings both in economic costs and GHG emissions.[41]

Roshani et al. 2012 used an elitist GA to create solutions for a single-optimization of a WDS design problem. An elitist GA is more selective about which populations are used to create combinations than a typical GA.[35] As in Wu et al. 2010b, environmental impacts were normalized into economic costs using carbon pricing. Costs included capital costs, operation, and GHG emissions. GHG emissions were only calculated from pumping energy based on the local electricity mix. The optimization was applied to a case study WDS expansion in Amherstview, CAN. Projections for decarbonization of this electricity mix were included. The study varied carbon prices and social discount rate in considering 18 different design scenarios. Either operation or capital costs dominated the different design scenarios. The study concluded that incorporating a low social discount rate or an aggressive carbon-pricing scheme had little effect on the design of the WDS expansion.[42]

Wu et al. 2012b used a GA to create solutions for a multiobjective optimization design problem. Objectives included minimization of economic costs and GHGs. The case study was adapted from *(39)*, where three storage tanks at the same elevation were pumped to from a source. Electricity emission factors (for pumping energy) and electricity prices were varied over time to reflect price increases and grid decarbonization. Both were found to have a significant effect on GHGs (emission factors) and economic costs (electricity prices), but optimal design options remained the same.[43]

4.4 Pipeline Construction Studies

This related literature has a strong focus on construction of pipeline systems used in the transportation of water, and includes both LCA studies and studies that simply measure outputs from equipment use in construction. The existing work details both invasive (open-trench) and non-invasive (horizontal directional drilling (HDD), pipe bursting) construction techniques.

Herz and Lipkow 2002 performed an LCA to determine the impacts of different pipe materials, pipe liners, and dig vs. no-dig technologies for pipe construction. Pipe maintenance is included in the form of pipe re-lining. Ductile iron (DI) and polyethylene (PE) pipes are considered in the study. No-dig technology inputs are assumed to be negligible. Sewers are also considered with concrete pipe material. No-dig technologies with concrete-relining for DI pipes are found to be the best option in reducing GHG emissions for water distribution. The study was the first to apply LCA to pipeline construction, but lacked details for equipment and material use in the construction processes.[44]

Ariaratnam and Sihabuddin 2009 determined the air emissions of equipment use in constructing a 106m length of PE piping. The study compared the total air emissions of hydrocarbons, NO_x, SO_x, PM, CO_2, and CO for open-trench construction and pipe-bursting construction. The air emissions did not include life-cycle considerations. Pipe bursting is a non-invasive pipeline replacement technique where the existing pipe is sliced open by a rolling-blade traveling down the pipe. An expander follows the blade that places a new, usually plastic material, pipe within the cut pipe. Significant reductions in emissions were found using pipe bursting in place of open-trench, often over a factor 5 in reductions.[45]

Piratla et al. 2012 performed an LCA for a pipeline intended for drinking water distribution with a focus on pipeline construction. The study's scope included materials production, construction, and water distribution. Material production and construction were limited to the pipeline. The study analyzed a 500ft length of pipe for CO_2 emissions through the product life for 4 different pipe materials: 2 types of PVC, high-density PE (HDPE), and DI. An HDD construction method was detailed for water transportation applications. Pumping energy and effects of pipe degradation were included in the usage phase. Pipe repair was included based on an estimated number of breaks, and the pipe was repaired using clamps and open-trench construction. The operation phase and pumping energy dominated environmental impacts. The study incorporated detailed pipe construction and HDD methods into an LCA study, but had a limited scope in analyzing only a short segment of piping.[46]

Du et al. 2013 performed an LCA for an isolated length of pipe for water distribution and wastewater collection. The study's scope included materials production, construction, and distribution/collection for 6 different pipe materials: PVC, DI, cast iron, concrete, reinforced concrete, and HDPE. Materials production was limited to pipe manufacturing. Construction was assumed to be open-trench. The distribution environmental impacts were based solely on head losses from pipe degradation. The study compared 10 different pipe sizes for each material where pipe production dominated the GHG emissions. This study assessed new pipe materials in reinforced concrete and concrete pipes, but omitted several important facets of a case study WDS LCA that could significantly alter the results, namely pumping energy.[47]

4.5 Water-Energy Sustainability Tool

The only comprehensive water infrastructure environmental assessment tools that are publicly available are WEST and, for wastewater systems analysis, WWEST.[48] WEST allows utility decision makers to incorporate LCA into determining air emissions and energy use of water infrastructure systems. Based on user inputs for construction, maintenance, equipment use, and electricity consumption, the tool can generate results that are specified by life-cycle phase, water supply phase, life-cycle activity, and water source of scenario. Figure 5 shows a visual representation of the elements included in the WEST model and tool.

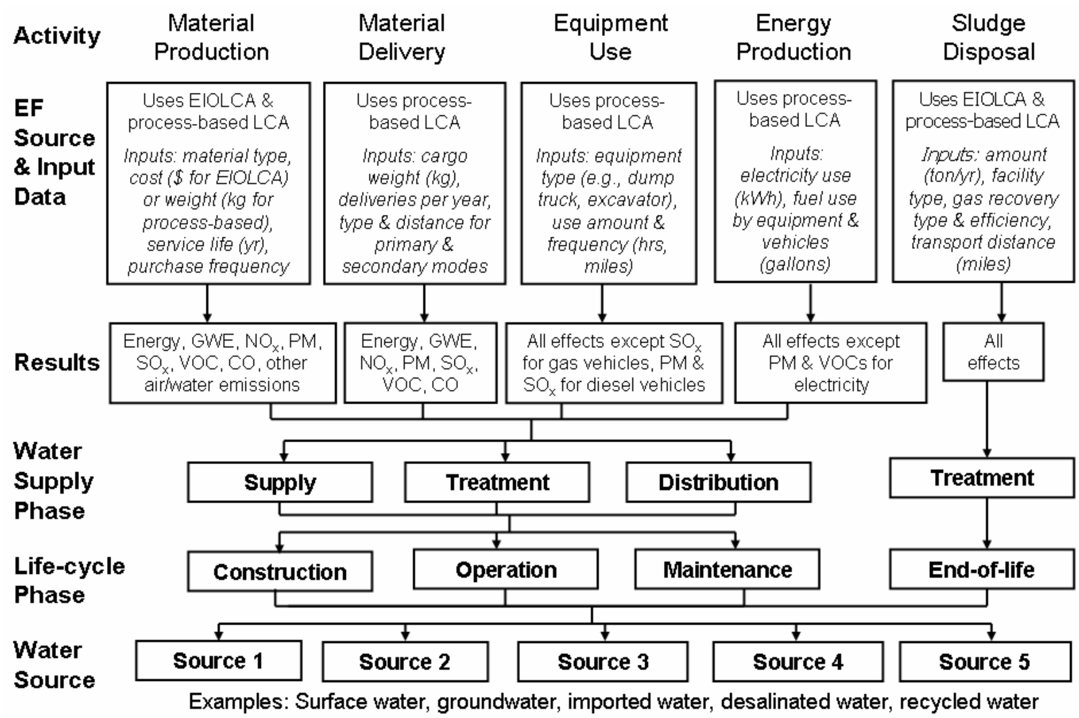

Figure 5. Structure of WEST model and tool. Source: (48).

The environmental metrics tracked in WEST are air emissions ($CO_{2(eq)}$, NO_X, SO_X, carbon monoxide (CO), PM, and volatile organic compounds (VOCs)) and energy use (electricity and primary energy). WEST uses hybrid LCA methods to allow the user to customize what materials, processes, and local conditions contribute to overall environmental impacts. In the material selection, WEST provides options for over 150 different materials that are assessed using LCA methods.

WEST is highly comprehensive and inclusive, but lacks specific details that are essential in an accurate, detailed LCA of drinking water utilities. WEST applies the best available LCA data for assessing certain aspects of WDSs, such as treatment, but some infrastructure elements are based on less accurate LCA data, and ask for user input that would be difficult for utilities to quantify. For pipes, WEST provides 11 options for materials, but all of these are based on EIO-LCA data that is defined by general sectors (both DI and steel piping could be lumped into the "iron, steel pipe and tube manufacturing" sector), and requires a monetary input to generate LCA results. This financial valuation would be difficult for utilities to quantify that have piping in the ground that is, in some cases, almost 100 years old. In the example of the case study utility discussed in Chapter 5, the case study utility representatives are capable of providing information on every piping segment in their system based on pipe size, length, and type. To find accurate costing information for this entire system is impractical.

WEST does not directly address issues that can compound a utility's environmental footprint, such as losses in distribution, and does not consider the different infrastructure elements' performance over the product's lifetime, such as pipe degradation. This research seeks to improve on that work by creating solutions and a tool for performance-based problems through the breakeven analysis, which is described in Chapter 6. WEST only includes an environmental perspective in the results, whereas this dissertation combines environmental impacts with economic costs to identify cost-effective solutions for reducing GHG emissions.

4.6 Related Literature Synthesis

Many of the existing WDS studies, both those that address design problems and those that provide LCAs, draw from the same data sources, most notably for pipes, where several studies cite the same source.[36,38,42,46,47] This pipe-data source is a non-peer reviewed publication that used a combination of existing studies and manufacturing data, but provides very little information about the actual methodology used in determining the embodied energy of piping.[49] This dissertation sought out new pipe LCA sources that provided the highest level of detail possible.

Existing WDS LCA studies do not present a comprehensive assessment. Many entities are missing or analyzed with general estimates. Only one study has included the potential impacts of water storage in their LCA, but this was based on general economic costs that were simply put into a standard EIO-LCA model.[39] This dissertation assesses water storage based on specific as-built drawings, and the case study utility provided volumes for every water facility available. Water wells and pumping facilities, perpetually omitted in existing research, are included in this dissertation. Steel pipes are only assessed using a general EIO-LCA sector in existing literature, which is a common element of U.S. WDSs.[50]

Leaks, or water losses in distribution (non-revenue losses), are only given limited attention in the existing literature.[30,34] In both studies, leaks are presented as a portion of the total footprint and are not discussed further. This dissertation strives to create more detail for leaks, as they have become a major focus for WDSs both in the United States and worldwide.[13] Specifically, this effort entails assessing how the environmental impacts of leaks can affect maintenance and pipe replacement scheduling.

Previous studies often have focused on solving theoretical problems or presenting results that are not intended to be immediately useful to utilities. This dissertation presents results in a utility-relevant manner, and the tools and comparisons derived from these results are geared to be beneficial to utilities seeking to reduce their GHG footprint.

5. Life-cycle Inventory

5.1 Description of Case Study Utility

The U.S. WDS assessed in this study supplies almost 10 billion gallons (37.8 GL, 37,000 acre feet) annually to over 23,000 service connections. The utility serves a metropolitan area located in a mountainous region in the Western United States. The service area sits mostly on a valley floor above an aquifer. The aquifer, which is the sole source of drinking water for the utility, is a pristine freshwater source that requires no filtering and only minimal chlorination for treatment. Water wells pump from the aquifer, while cylindrical steel tanks and concrete reservoirs store the water at higher elevations to create a gravity-fed distribution system. Booster pumps are used to transport water to higher elevations that cannot be reached by the pumps at water wells.

The utility has mimicked the city's development, expanding towards the higher elevations from the valley floor. In this development, the utility annexed several smaller water systems, which had to be connected to existing service lines, creating a system not optimally designed to service a large area. Therefore, the WDS has no dedicated transmission mains so that water destined for storage travels through the same pipes as water delivered to customers. This results in smaller pipes experiencing high-pressure loads that were not sized with this intention.

The general design and operational capacity of the WDS, coupled with an easily accessible, inexpensive and plentiful freshwater source, has resulted in high water losses. The case study utility experiences 40% losses in distribution, and it is assumed that the majority of these losses are from leaks (real losses). These losses are not as great of a concern as they may be for utilities with strained water supplies because most water losses eventually recharge the aquifer below the municipality. However, the losses that recharge the aquifer must still be pumped and treated before reaching the consumer, which compounds the energy and emission demands of the delivered water to the customer. Preventing losses such as these would avoid any added emissions in pumping and treatment. The treatment and pumping purchases are also wasted with these losses and present significant opportunities for economic cost savings, but difficult barriers exist to achieving these savings, which are discussed in Chapter 8.

The case study utility has many atypical elements that are not commonly found amongst U.S. WDSs, namely the pristine water source and extremely high level of distribution losses. However, the piping materials, water storage, well facilities, pumping facilities, and construction techniques are similar to those of many U.S. WDSs. These common WDS aspects are assessed in this research.

5.2 Life-cycle Inventory

This study focused on four major engineering aspects: water wells, water storage, pumping, and pipelines. Each of these aspects is described in detail within this chapter. The specific data sources used for each product/process analyzed are listed in Table 4.

Product/Process	**LCA Method**	**Source**
Steel materials (tank use)	Process	Density: *(51)*, embodied GHGs: *(52)*.
Crushed Rock	EIO-LCA	Purchaser price: *(53)*, density: *(54)*.
Pea-gravel	EIO-LCA	Purchaser price: *(53)*, density: *(55)*.
Concrete	Process	Embodied GHGs: *(56)*.
Steel rebar	Process	Density: *(57)*, embodied GHGs: *(52)*.
Formwork	EIO-LCA	Purchaser price: *(57)*.
Steel pipe	Process	Density: *(58)*, embodied GHGs: *(52)*.
PVC pipe	Process	Embodied energy: *(59)*, density: *(60)*, *(61)*.
Ductile iron concrete-lined pipe (DICL)	EIO-LCA	Purchaser price: *(57)*, density: *(62)*.
Cast iron pipe	EIO-LCA	Purchaser price: *(57)*, density: *(63)*.
Polyethylene pipe	Process	Embodied energy: *(64)*, density: *(65)*.
Concrete asbestos pipe	EIO-LCA	Purchaser price: *(66)*, density: *(67)*.
Pump	EIO-LCA	Purchaser price: provided by the case study utility
Asphalt	Process	Embodied energy: *(68)*, density: *(69)*.
Shipping	Process	Emission factors: *(70)*.
Chlorine	Process	Embodied GHGs: *(71)*.

Table 4. Method and data details for the LCI.

Where EIO-LCA was used, the purchaser price was adjusted to the model year (2002). All costs were adjusted using the Bureau of Labor Statistics' inflation calculator, which uses the Consumer Price Index.[72] For the products/processes listed in Table 4 that utilized EIO-LCA, the specific economic sectors assessed are listed in Table 5. All assessments that used EIO-LCA were performed with the 2002 purchaser price model.[73] Table 5 also displays the RSMeans sectors for those products whose economic costs were found using RSMeans.[56] Other sources for purchaser prices for materials come directly from manufacturer's price lists. For concrete asbestos pipes, which are no longer produced or installed, the closest available cost was for reinforced concrete pipe. This purchaser prices was used in a related "concrete pipe" sector of EIO-LCA (Table 5).

Product/Process	RSMeans Sector	EIO-LCA Sector
Pea-gravel, crushed rock	N/A	Stone mining and quarrying
Formwork	Radial walls (03110-455-4050), Elevated slab (03110-420-1050, Round fiberglass (03110-410-0600), Exterior walls (03110-455-2450)	Veneer and plywood manufacturing; Plastics pipe and pipe fitting manufacturing
DICL, cast iron pipes	Water supply, concrete lined ductile iron pipe (02510-730)	Iron, steel pipe and tube manufacturing from purchased steel
Concrete asbestos pipe	N/A	Concrete pipe, brick and block manufacturing
Pumps	Pumps, installed in wells (02520-510-(1510-2000))	Pump and pumping equipment manufacturing

Table 5. Sector details for products and processes evaluated using EIO-LCA.

Shipping was individually calculated for piping materials and asphalt as the specific supplier locations were identified by the case study utility or assumed. A class 8b truck (tractor trailer) was used in the calculations. All other WDS elements included shipping in the methods or data sources used.

5.3 Piping Materials

GHG emissions from materials used in distribution mains were found from the specific lengths, sizes, and material types that were detailed by the participating utility's geographic information system (GIS). The GIS provided pipeline specifics based on each pipe segment within the distribution system. Each pipe segment's embedded energy was found by applying a calculated energy density per-unit-length based on the segment's size and material type. Six material types were studied based on the utility's inventory: cast iron, concrete-lined ductile iron (DICL), PE, concrete asbestos, PVC, and steel.

The sources used in determining the energy densities are listed in Table 4, but specific values are displayed in Tables 6-11. Cast iron pipes were assumed to have the same costs as DICL pipes. Densities differentiated the DICL and cast iron pipes in the GHG outputs. All GHG emissions for the entire study are based on the 100-year $CO_{2(eq)}$ value.

In the case of PE and PVC pipes, it was assumed that the pipes were produced using only electricity, an assumption borne out by an existing LCA study.[74] The electricity mix for production was based on the supplier location for the utility studied. The supplier's electricity mix was primarily coal (82%) and natural gas (16%).[74] Electricity emission factors included the entire product life-cycle, and were taken from a California Energy Commission (CEC) report.[76] Full details of electricity mixes and emission factors are presented in Appendix A. When data were unavailable for certain pipe sizes, estimates were created by extrapolating from existing values.

The pipes assessed using EIO-LCA included all industry interactions up to and including production of the product, including recycled material inputs. Steel pipe, assessed using World Steel data, included all aspects of the product's life, excluding any inputs during operation but recycling. World Steel is a non-profit organization that provides strategic solutions for the entire steel industry, of which the LCA of different steel products is a focus. Data is publicly available from World Steel on request. The recycling rate used by World Steel was 85%.[52] For PVC pipes LCA data included all processes up to and including pipe production. This did not include recycled material due to lack of data.[59] HDPE pipes included impacts up to and including pipe production, but did not assess end of life as it was assumed underground pipes were abandoned in the ground.[64]

Transportation was included for pipe materials from the supplier location indicated by the case study utility. Although many pipe materials were modeled using EIO-LCA, which includes shipping, the utility studied noted that their piping materials were shipped from a region outside the EIO-LCA model's boundary. All shipping emissions were calculated based on the material density, length of material, and LCA shipping emission factors.[70]

Diameter (mm)	Diameter (in)	Density (kg/m)	Material Cost 2012 ($/m)	Embodied Energy (MJ/kg)	Embodied GHGs (kg $CO_{2(eq)}$/kg)
50	2	11.80	23.74	35.80	2.796
75	3	13.84	25.98	33.40	2.608
100	4	16.24	28.43	31.16	2.433
150	6	23.84	33.29	24.86	1.941
200	8	15.05	45.07	53.31	4.163
250	10	40.38	69.20	30.50	2.382
300	12	51.85	72.75	24.97	1.950
350	14	60.20	80.42	23.78	1.857
400	16	73.46	114.08	27.64	2.159
450	18	85.23	127.17	26.56	2.074
500	20	100.58	138.39	24.49	1.913
600	24	120.39	185.15	27.37	2.138
750	30	172.10	280.92	29.06	2.269

Table 6. Details for DICL piping.

Nominal Diameter (mm)	Nominal Diameter (in)	Density (kg/m)	Material Cost 2012 ($/m)	Embodied Energy (MJ/kg)	Embodied GHGs (kg $CO_{2(eq)}$/kg)
3	0.13	0.36	18.50	15.45	1.30
6	0.25	0.63	18.66	15.45	1.30
9	0.38	0.85	18.83	15.45	1.30
12	0.50	1.19	19.00	15.45	1.30
18	0.75	1.68	19.34	15.45	1.30
25	1.00	2.5	19.74	15.45	1.30
32	1.25	3.38	20.15	15.45	1.30
38	1.50	4.05	20.51	15.45	1.30
50	2.00	5.44	21.26	15.45	1.30
63	2.50	8.62	22.10	15.45	1.30
75	3.00	11.3	22.91	15.45	1.30
88	3.50	13.6	23.81	15.45	1.30
100	4.00	16.1	24.68	15.45	1.30
125	5.00	21.7	26.63	15.45	1.30
150	6.00	28.3	28.73	15.45	1.30
200	8.00	42.6	33.66	15.45	1.30
250	10.00	60.3	41.89	15.45	1.30
300	12.00	73.8	50.12	15.45	1.30
350	14.00	81.3	57.46	15.45	1.30
400	16.00	97.6	65.87	15.45	1.30
450	18.00	105	76.68	15.45	1.30
500	20.00	117	87.90	15.45	1.30
600	24.00	141	151.48	15.45	1.30
750	30.00	177	198.24	15.45	1.30

Table 7. Details for steel piping.

Nominal Diameter (mm)	Nominal Diameter (in)	Density (kg/m)	Material Cost 2012 ($/m)	Embodied Energy (MJ/kg)
50	2	2.22	4.15	37.09
75	3	2.50	8.83	34.17
100	4	2.83	9.61	31.47
150	6	5.81	19.08	26.08
200	8	9.98	32.91	21.62
250	10	15.05	49.75	17.92
300	12	21.46	70.32	14.85
350	14	29.03	48.06	12.31
400	16	37.82	63.59	10.20
450	18	47.67	80.42	8.45
500	20	58.80	99.12	7.00
600	24	84.90	140.26	4.61
750	30	131.85	216.94	2.24
900	36	191.33	306.71	1.09
1050	42	262.27	418.92	0.53
1200	48	344.52	542.35	0.26

Table 8. Details for PVC piping.

Nominal Diameter (mm)	Nominal Diameter (in)	Density (kg/m)	Material Cost 2012 ($/m)	Embodied Energy (MJ/kg)	Embodied GHGs (kg $CO_{2(eq)}$/kg)
100	4	80.38	10.11	1.36	0.14
150	6	93.79	14.1	1.62	0.17
200	8	109.44	21.3	2.10	0.22
250	10	127.70	27.6	2.33	0.25
300	12	149.00	35.4	2.57	0.27
350	14	170.30	45.4	2.88	0.31
375	15	190.72	51.9	2.94	0.31
450	18	250.32	73.9	3.19	0.34
600	24	399.32	136.7	3.70	0.39

Table 9. Details for concrete asbestos piping.

Nominal Diameter (mm)	Nominal Diameter (in)	Density (kg/m)	Material Cost USD 2012 ($/m)	Embodied Energy (MJ/kg)
25	1	6.84	8.28	25.31
50	2	7.60	9.21	25.31
100	4	9.53	11.54	25.31
150	6	11.95	14.45	25.31
200	8	14.97	18.10	25.31
350	14	39.49	47.69	25.31
375	15	43.48	52.50	25.31
450	18	65.25	78.55	25.31

Table 10. Details for PE piping.

Nominal Diameter (mm)	Nominal Diameter (in)	Density (kg/m)	Material Cost USD 2012 ($/m)	Embodied Energy (MJ/kg)	Embodied GHGs (kg $CO_{2(eq)}$/kg)
50	2	4.3	22.82	94.46	7.38
100	4	8.4	28.43	60.24	4.70
150	6	14.1	33.29	42.02	3.28
200	8	23.1	45.07	34.73	2.71
250	10	33.3	69.20	36.99	2.89
300	12	43.2	72.75	29.98	2.34
400	16	77.65	114.08	26.15	2.04

Table 11. Details for cast iron piping.

5.4 Pipe Construction

In the LCA of the case study utility's WDS, all pipeline construction was assumed to be performed using open-trench techniques. Recently the case study utility has experimented with non-invasive construction technologies, but not on a significant scale. Open-trenching involves excavating all materials located where a pipe is to be laid. This method is the original and most widely used approach for pipe maintenance and construction. This process has been detailed by a separate study, where environmental impacts from equipment use in construction have been assessed.[45] The results of the open-trench study were used to quantify pipeline construction impacts in this study. The open-trench study recorded equipment use for a 348 ft (106 m) pipeline at a depth of 6.9 ft (2.1 m). The pollutant emissions and energy use were found on a per-unit-length basis and applied to the total length of piping in the WDS. Table 12 displays the equipment use details for the construction process. It was assumed that all piping in the WDS was placed at the same depth used in the open-trench study. All excavated materials in trenching were assumed to be used as backfill or disposed of locally. Transportation of these materials was not included in the analysis.

Equipment	Rating (hp)	Usage (hrs)	Load Factor	CO_2 (kg/m)
Excavator	90	22	100%	11.1
Excavator	90	4.5	75%	1.7
Water Pump	10	20	100%	1.1
Loader	130	6	60%	2.4
Soil Compactor	80	6	100%	2.7
Paver	158	1.5	100%	1.2
Asphalt Compactor	174	1	100%	0.9

Table 12. Equipment use details for open-trench construction. Source: (45).

In the breakeven analysis, horizontal directional drilling (HDD) and open-trench are the two alternatives that exist for pipeline replacement. HDD is a technique that avoids invasive trenching by drilling horizontally to place piping. The technique has grown in popularity worldwide among utilities and is increasing in use in the United States. A separate study performed an LCA of 499 ft (152 m) pipeline that was placed using HDD at a depth of 3.9 ft (1.2 m).[46] The equipment use and impacts from this HDD LCA were calculated on a per-unit-length basis and applied to the analysis length in the breakeven analysis. Table 13 displays the equipment use details for the HDD construction methods used in this dissertation. Although the pipeline depth in the HDD LCA was less than the open-trench construction, it was assumed that equipment use varied very little with construction depth. Pipeline depth and equipment use for HDD is analyzed in detail in another construction-costs study where construction costs remain relatively fixed with depth in HDD construction.[77]

Equipment	Rated power (kW)	Usage (hrs)	Load Factor	CO_2 (kg/m)
Backhoe	63	8	63%	1.9
Excavator	37	19	85%	3.1
Crew Truck	261	3	50%	1.8
Drill Rig	142	24	73%	11.6
Roller	22	3	40%	0.1

Table 13. Equipment use details for HDD construction. Source: (45).

Asphalt impacts were excluded from the original construction of the pipelines, but are included in pipe replacement. The asphalt inputs are used in the breakeven analysis. The case study utility was required to make all trenches 8 ft (2.44 m) wide. Asphalt material depth was assumed to be 0.15 in (0.38 cm). For HDD, the necessary trench was fixed for any pipe length, and the length of the trench was assumed to be 10 ft (3.05 m). Open-trench asphalt material volume varied by the length for pipe replacement. The embodied energy of asphalt production was taken from *(68)*, which includes bitumen production, aggregate drying, mixing, and asphalt storage. The density used in shipping calculations was 145 pcf (16 kg/m^3).[69] The shipping distance was based on the closest aggregate mine.[78] The asphalt production was performed locally using the same electricity mix used for pumping energy emissions.

The utility estimated that 0.3% of all WDS pipes were repaired each year. This equates to about 0.93 mi (1,500 m) of piping. It was assumed that this piping was replaced using open-trench construction. Asphalt materials (for repairing roads above pipes) were included in the maintenance assessment. The dimensions of the necessary trench were assumed to be the same as piping installation. The case study utility could significantly reduce leak distribution losses by increasing the replacement rate of piping. This increased replacement could substantially reduce GHG emissions, which is discussed later in this chapter in the LCI results and further analyzed in Chapter 6.

5.5 Water Storage: Tanks and Reservoirs

The participating utility uses two types of water storage: concrete reservoirs and steel tanks. Concrete reservoirs are based on as-built blueprints provided by the utility for a 600,000 gal (2.28 ML) storage facility. The term "reservoir" was applied by the case study utility to these storage facilities, but the actual design of the concrete reservoirs is much different than the traditional definition of an artificial lake. Concrete reservoirs, as defined by the case study utility and the term used in this dissertation, consist of a cylindrical storage tank supported by four internal columns resting on a foundation. These elements are made of reinforced concrete. A catch basin was also assessed from the as-built documents, and only included concrete. The catch basin size remained fixed for all of the utility's reservoirs when calculating the LCI. Table 14 shows the concrete inputs for the 600,000 gal facility as quantified from the case study utility's as-built documents.

Concrete	**Volume (yd^3)**	**$CO_{2(eq)}$ ton/yd^3**	**$CO_{2(eq)}$ (ton)**
Walls	207	0.73	3.28
Foundation	274	0.73	4.36
Roof	132	0.73	2.10
Columns	4.58	0.73	0.07
Catch Basin	1.10	0.73	0.02

Table 14. Concrete LCI details for the 600,000 gal (2.28 ML) case study utility concrete reservoir.

Concrete impacts were calculated using the Green Concrete LCA Tool, which includes all aspects for concrete production.[56] The concrete was assumed to be produced locally, and the electricity mix reflected this. Concrete was assumed to be made from Type II Portland Cement (moderate sulfate resistance) with a cement-water ratio of 0.35 and 28.8 lb of cement per ft^3 of concrete (461 kg/m^3). Cement was produced using dry processing and it was assumed fuel inputs were 100% coal. The concrete used in the design required a 4000 psi (28,000 KPa) rating. Rebar was assessed using World Steel data, where the study used the same methods as for steel pipes and was based on a recycling rate of 85%.[52]

Formwork was estimated for all concrete structures, where plywood was assumed to be used, except in the case of columns where a prefabricated plastic cylinder was used. Construction equipment use was estimated from *(57)*, and emission factors were taken from the EPA.[79] These emission factors are for gasoline and diesel industrial engines without emission controls. In constructing the concrete reservoir, it was assumed that a concrete vibrator and concrete pump were necessary. The specifics and usage of this equipment is detailed in Table 15.

Equipment	**Engine**	**Rating (hp)**	**Load Factor**	**Usage (hr)**	**$CO_{2(eq)}$ (kg/gal capacity)**	**Source**
Gas Engine Vibrator	Gasoline	6.5	1	6.5	3.45E-05	*(80)*
Concrete Pump	Diesel	183	0.8	3	3.82E-04	*(81)*
Small Crane	Diesel	20	0.5	8	1.05E-04	*(82)*
Arc Welder	Gasoline	8.0	1	32	3.10E-04	*(83)*

Table 15. Reservoir and tank construction equipment specifics.

To find the total life-cycle GHG emissions from concrete reservoirs for the case study utility, the LCI results from the as-builts were scaled up to the varying reservoir sizes. Reservoir capacity totaled over 8.2 million gallons (31 ML). Each reservoir was assessed individually. Concrete varied based on the estimated volume used, and formwork, rebar, and equipment use were adjusted linearly based on the capacity of the reservoir. For concrete, the height was assumed to be constant for all reservoirs, and the diameter varied with the storage volume of the facility. Thickness of walls, foundations, and roofs were assumed to be constant. Concrete and rebar accounted for the majority of GHG emissions, which can be viewed in Section 5.9.

Steel tank impacts were calculated based on as-builts provided by the utility and an on-site visit. The as-builts provided general details for a 400,000 gal (1.52 ML) storage facility, but did not offer specifics on the quantities or type of steel used in the facility construction. With knowledge of the dimensions of the facility, a steel tank industry representative provided specifics on the typical steel materials used in this type of design.[84] Quantity 2 steel sheets were assumed to be used (4 ft (1.2 m) by 10 ft (3.1 m)) with a thickness of 0.25 in (.64 cm) according to American Water Works Association standards.[85] Table 16 shows the dimensions for the typical steel sheet used in the LCI of steel tanks.

	Length (ft)	Adj. Length (ft)	Height (ft)	Thickness (in)	$CO_{2(eq)}$ (kg/sheet)
Steel Sheet (typ.)	4	3.67	10	0.22	942.13

Table 16. Typical steel sheet details. Typical signifies the same steel sheet is used throughout the design and construction of the storage tank. Source: (84).

The steel sheets were lifted into place with a small crane and then welded together. The older steel tanks used by the case study utility are bolted, but these are rarely constructed anymore in the industry,[84] so it was assumed that welding was used in all tank construction. Two rings of sheets were needed to achieve the tank height, with an overlap of 2 in (5.1 cm) where steel sheets were welded. From this information, the total mass of steel could be estimated and applied to the process LCA data. Table 17 shows the details for total steel usage in the 400,000 gal tank.

	Surface Area (ft^2)	Total # of Sheets	Total Mass of Steel (ton)	$CO_{2(eq)}$ (kg/gal capacity)
Steel Inputs	9957.6	272	212.3	0.66

Table 17. Steel inputs for the case study utility's 400,000 gal tank.

Steel used in the tank designs was assumed to be plate steel and based on LCA data from World Steel. These data were based on a recycling rate of 85% and produced in North America.[52]

The tank rests on a bed of pea gravel 8 in (20 cm) deep, with a ring of 1.25 in (3.18 cm) crushed rock extending out 5 ft (1.5 m) from the tank walls. It was assumed that a small crane and arc welder were the necessary equipment to construct the steel tank, and the specifics are detailed in Table 15.

Steel tanks were scaled up from the as-builts to the different sizes used by the case study utility similarly to the concrete reservoirs. Steel tank storage capacity totals almost 1.6 million gal (6 ML). The same steel sheets were assumed to be used at each tank where the number of sheets varied based on the surface area. The volume of aggregates varied based on the diameter of the facility, but the depth remained constant. The equipment use was scaled up linearly from the original as-built estimates.

More details for how GHG emissions from water storage facilities were calculated and how these methods impacted the final results are discussed in Section 5.10.

5.6 Wells and Booster Pumps

Booster pumps include only the facility materials and equipment used in construction. The participating utility did not cite any scheduled maintenance needs to be included in the assessment for booster pumps. Booster pumps include the on-site pumps and a reinforced concrete shed to house the pumps. Dimensions for the shed were estimated from a site visit to be 30 ft (9.1 m) by 15 ft (4.6 m), with a height of 10 ft (3.1 m). Reinforced concrete was based on the same LCA data from concrete reservoirs (concrete and rebar inputs). Booster pumps were scattered throughout the WDS, and more were concentrated in areas where water needed to be pumped to higher elevations. All pumps were assumed to have a horsepower rating of 100 hp (74.6 kW). It should be noted that booster pumps are separate from well pumps. Specific sources for pump costs and EIO-LCA sectors can be found in Table 5. It was assumed that only a concrete vibrator, as detailed in Table 15, was used for a period of 6 hours in construction of the facility (4 hours for shed walls, 1 for the shed roof, 1 for the shed foundation). Formwork was also included from the sources detailed in Tables 4-5.

Water wells represented the entirety of the utility's water supply. The participating utility provided the number of wells in operation, well depth, diameter, pump rating, and number of pumps. The utility only uses open-ended pipes for wells, meaning that no screens are necessary to filter the water source. Well pumps were assessed using the same method as booster pumps, and ratings ranged from 25 to 300 hp (18.7-223.8 kW).

A general well design was used to determine column and casing specifics.[58] All casings were assumed to be PVC, and columns were assumed to be steel. In the chosen design, a casing creates a barrier between soil and the column, which transports the pumped water to the surface.

A shed similar to the booster pump facility was estimated for the well facilities based on a site visit. The equipment use in construction was the same as the booster pumps with the addition of a grout seal and excavation of the well. The grout seal added 1 hour of concrete vibrator use to the 4 hours used in the shed construction. A drilling rig was assumed for well excavation. The rig has a rating of 600 hp (447.6 kW) for a diesel engine, with an assumed 100% load factor for one hour of use.

The GHG emissions were totaled from data from the site visit and the general design plans. For wells, the same shed and column were assumed to be used at every facility. Well pumps varied based on power ratings. Casing and excavation equipment use varied based on the well depth. For booster pumps, the shed remained constant while the pumps varied based on the power rating and number of pumps at each facility.

5.7 Treatment

Treatment was calculated using WEST.[71] Total chlorine purchases for a single year were obtained from the case study utility, and this mass was inserted into the tool. The case study utility used 12% chlorine solution for treatment at the source (water wells).

5.8 Pumping Energy

The electricity mix for pumping energy was taken from *(86)* for the local electric utility that provides power to the case study utility. LCA emission factors for electricity generation were taken from a California Energy Commission report.[76] The emission factors were calculated for each individual power source contributing to the mix and then summed. These electricity sources were mainly powered by coal combustion (61%) and hydropower (34%).

5.9 Life-cycle Inventory Results

The LCI results are disaggregated into 8 different WDS elements. Results were tracked through each life-cycle phase and element of the WDS on a per-gallon basis, and scaled up based on the utility's annual water volume delivered to customers. A gallon was chosen as the functional unit as the case study utility, and other U.S. WDSs, typically track supply metrics in gallons and not SI units. The GHG footprint for the utility is calculated over a 50-year analysis period (Figure 6). Demand was assumed to be fixed for this time period. Pumping energy, treatment, and maintenance are annually accrued over the analysis period. Pipes, tanks/reservoirs, wells, booster pumps, and pipe construction only occur once and are distributed evenly over the analysis period.

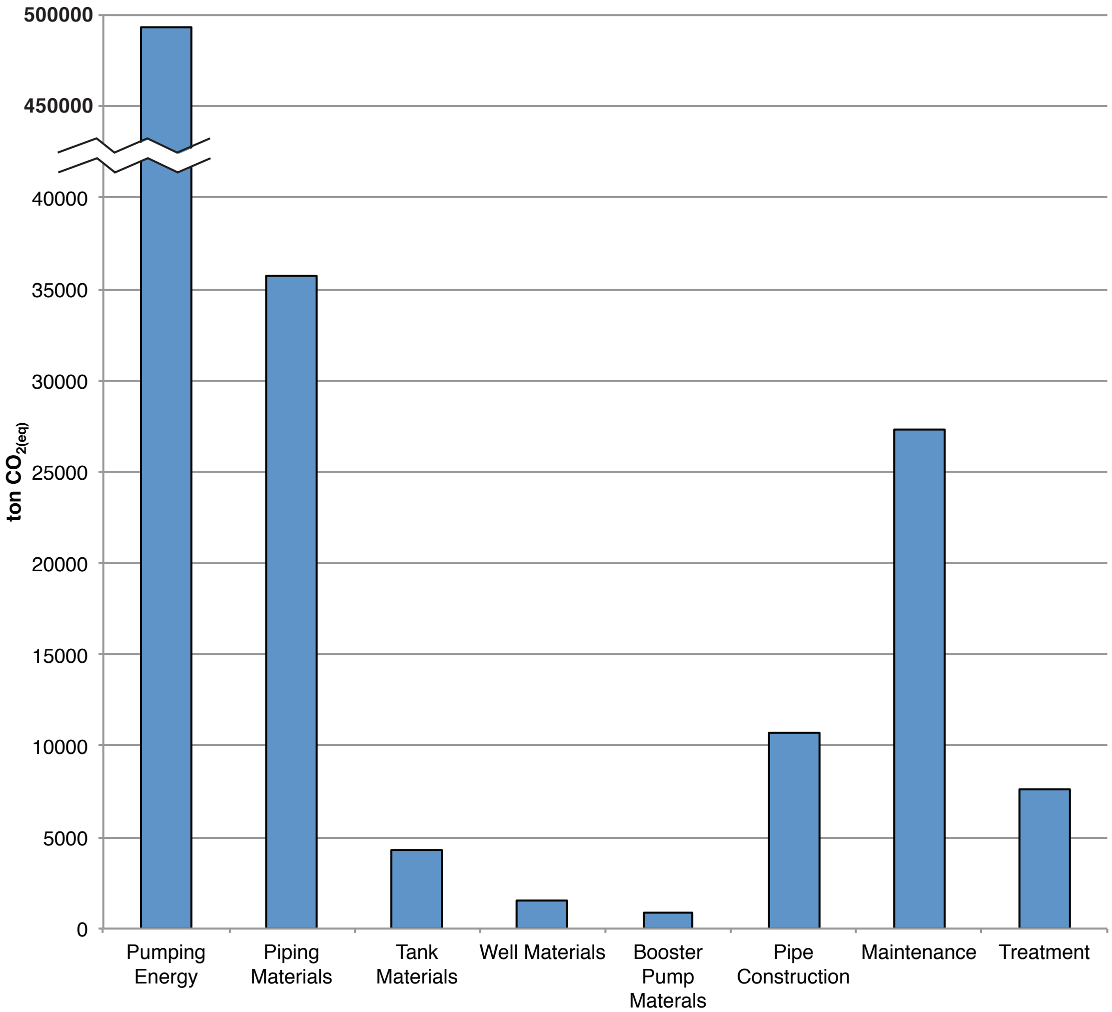

Figure 6. LCI results for a 50-year analysis period.

These results can also be viewed for the annual emissions for this same 50-year period in Figure 7.

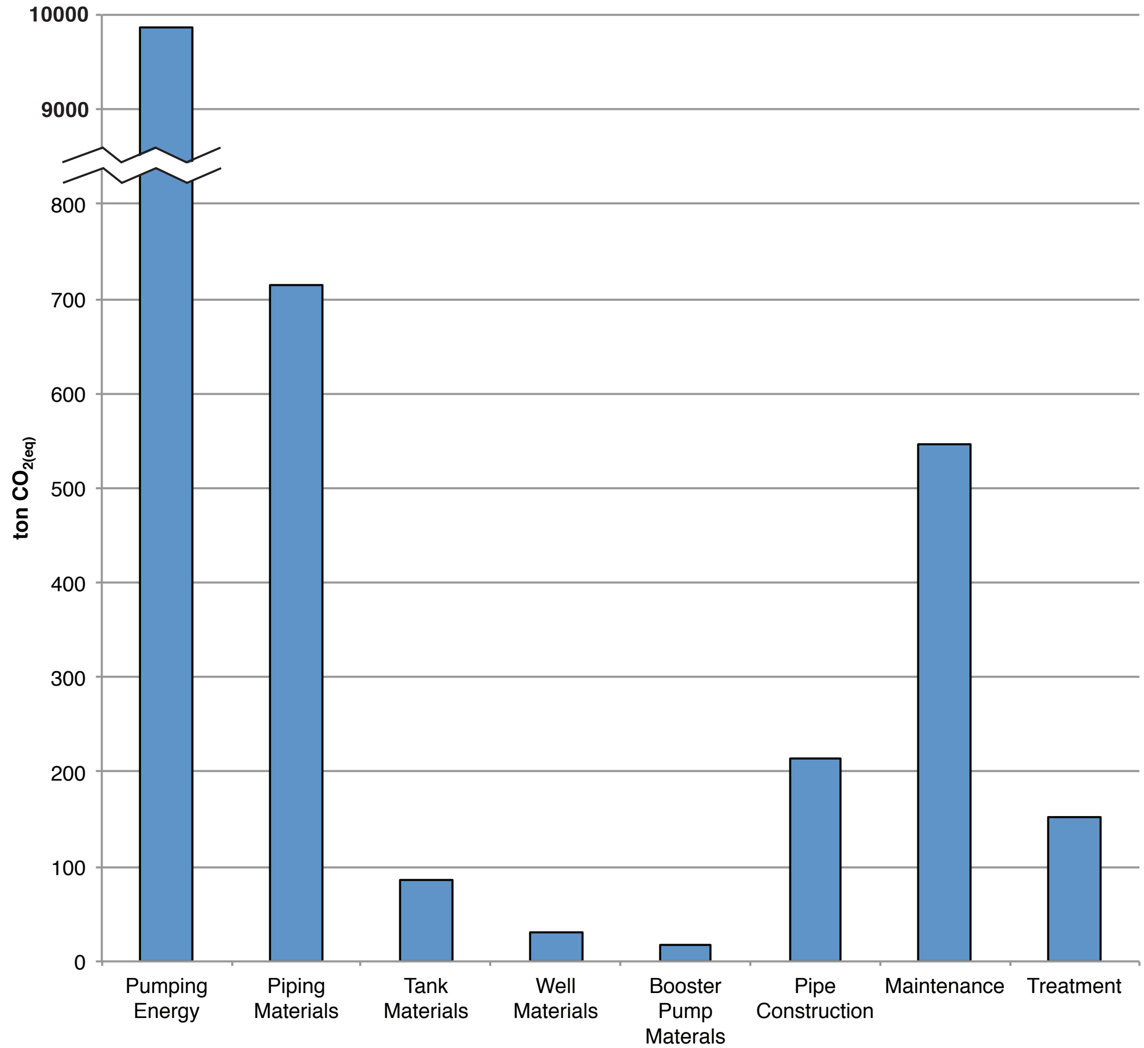

Figure 7. Annual GHG emissions for a 50-year analysis period for the case study utility.

Table 18 displays the detailed emissions for the 50-year analysis period disseminated by both total emissions and annual emissions. The GHG emissions are also detailed on a per-gallon basis from the case study utility's 2009 total consumption (10.4 billion gallons (39.4 GL) of water delivered to customers).

	ton $CO_{2(eq)}$	% of Total ($CO_{2(eq)}$)	Annual (ton $CO_{2(eq)}$)	% of Total (Annual $CO_{2(eq)}$)	Annual g $CO_{2(eq)}$/gal
Pumping Energy	493,334	84%	9,867	84%	0.949
Piping Materials	35,695	6%	713.9	6%	0.069
Tank Materials	4,325	1%	86.50	1%	0.008
Well Materials	1,586	0%	31.71	0%	0.003
Booster Pumps	892.8	0%	17.86	0%	0.002
Pipe Construction	10,727	2%	214.5	2%	0.021
Maintenance	27,324	5%	546.5	5%	0.053
Treatment	7,621	1%	152.4	1%	0.015
Total	581,503	100%	11,630	100%	1.12

Table 18. Detailed LCI results for a 50-year analysis of the case study utility.

Figure 8 displays a visual representation of the results from Table 18.

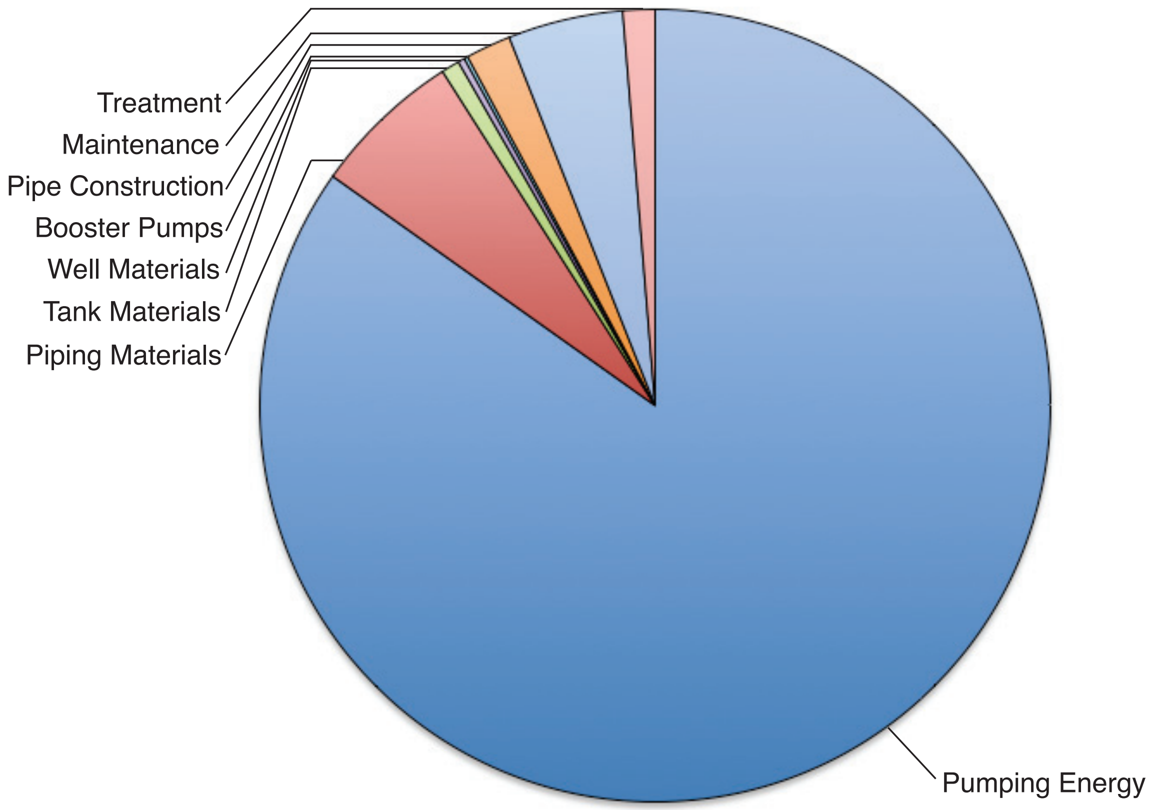

Figure 8. Allocation of total GHG emissions over a 50-year analysis period as detailed by Table 18.

5.10 Life-cycle Inventory Results Discussion

Pumping energy makes up the majority (84%) of the total GHG footprint for the 50-year period. The allocation of emissions remains the same when emissions are detailed on an annual basis. The pumping energy may be higher than in other U.S. utilities because of the substantial leaks in distributing water. The utility studied reported that it lost roughly 40% of water delivered to customers. A study of a water and wastewater utility in Sydney, Australia determined that pumping energy emitted 24% of all GHGs.[26] Another study calculated that direct energy inputs (pumping) accounted for 65% of the total energy demand of a water and wastewater utility in Kalamazoo, MI.[32] An LCA found that pumping energy composed 95-98% of total GHG emissions, where tanks and pipes emitted the remaining 2-5%.[40]

Since the utility studied is using a very clean water source by comparison to many other U.S. utilities, the treatment impacts are minimal (1%). A study examined a Southern California utility where treatment of an imported freshwater source accounted for ~10% of total energy consumption.[33] The same authors found that a different freshwater source only required 1.5-3% of total energy demand, which is closer to the results of this dissertation.[27] The Australian study found filtration to emit 11% of total GHGs.[26] Every water source will require different inputs, and significant variations can be expected.

As discussed in the literature review, circumstances for evaluation in each of the existing studies vary significantly, including methodology, scope, and geographical considerations. Treatment and pumping inputs will differ for every utility based on the quality, proximity, and elevation of the water source. This is made evident in a similar WDS LCA, where the study compared imported freshwater to desalinated water for consumption. The imported water required low treatment inputs but large pumping inputs to transmit the water over long distances. The desalinated water was located near the end consumer, needing little pumping, but required intensive treatment. Overall, the desalinated water was more than double the imported water in GHG intensity.[31] The two cases revealed how a utility's GHG footprint can be highly dependent on different WDS elements. This must be considered when applying the methods in this research to other WDSs.

Piping materials accounted for the second largest contributor to emissions (6%). Figure 9 shows the length of piping and GHG emissions disseminated by specific materials.

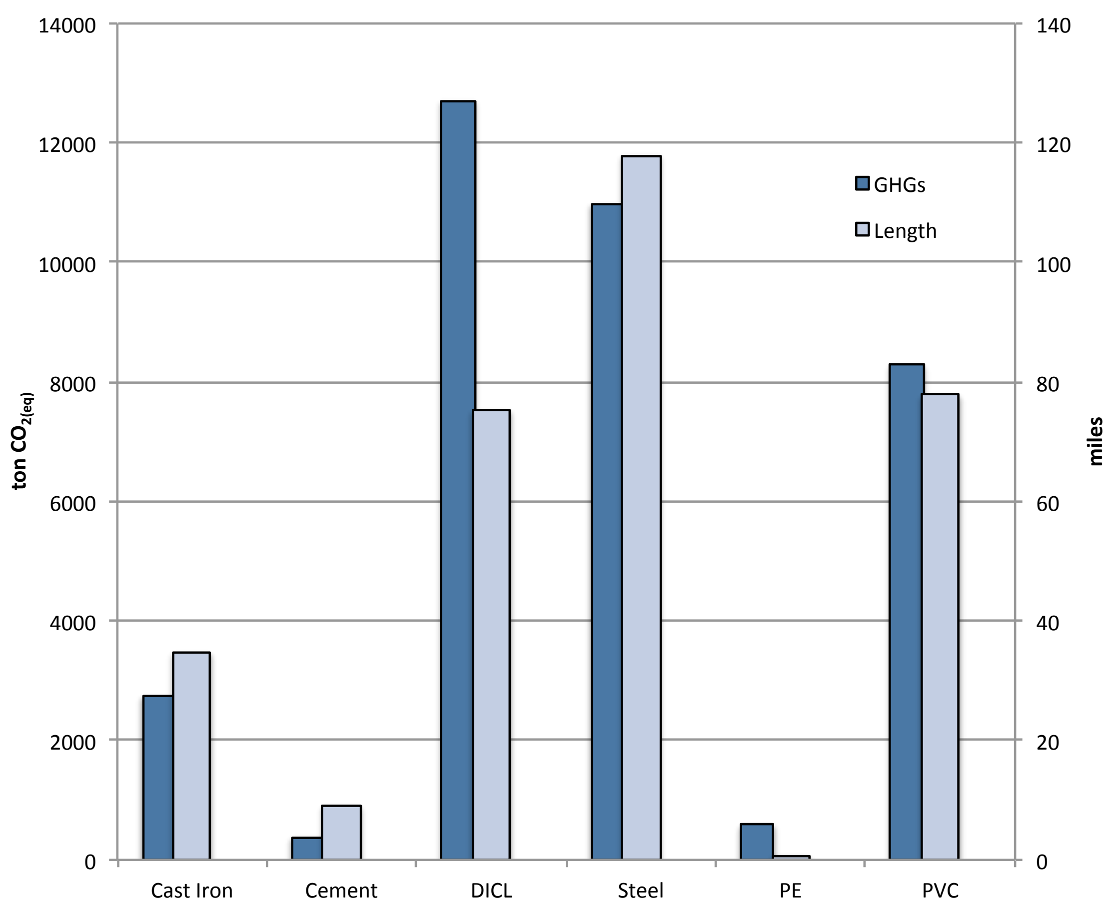

Figure 9. LCI results for pipe materials.

The case study utility has for over 300 miles (480 km) of pipes. Steel composes the majority of pipes. The case study utility noted that DICL is the material for the majority of the new pipes installed in the system. PVC pipe was often installed between 1980 and 2000 as the city expanded into the surrounding hills. The case study utility stated that plastic pipes have durability issues in a system with large variations in pressure, which the case study utility experiences (ranging from 40 to 130 psi (280 to 900 kPa)). Steel represents 37% of the total length and 31% of the total GHG emissions. DICL is the next highest length (24%), but a higher portion of GHGs (36%).

Maintenance impacts account for 5% of the totals. Figure 10 shows the detailed emissions by each contributing element to the case study utility's annual maintenance emissions.

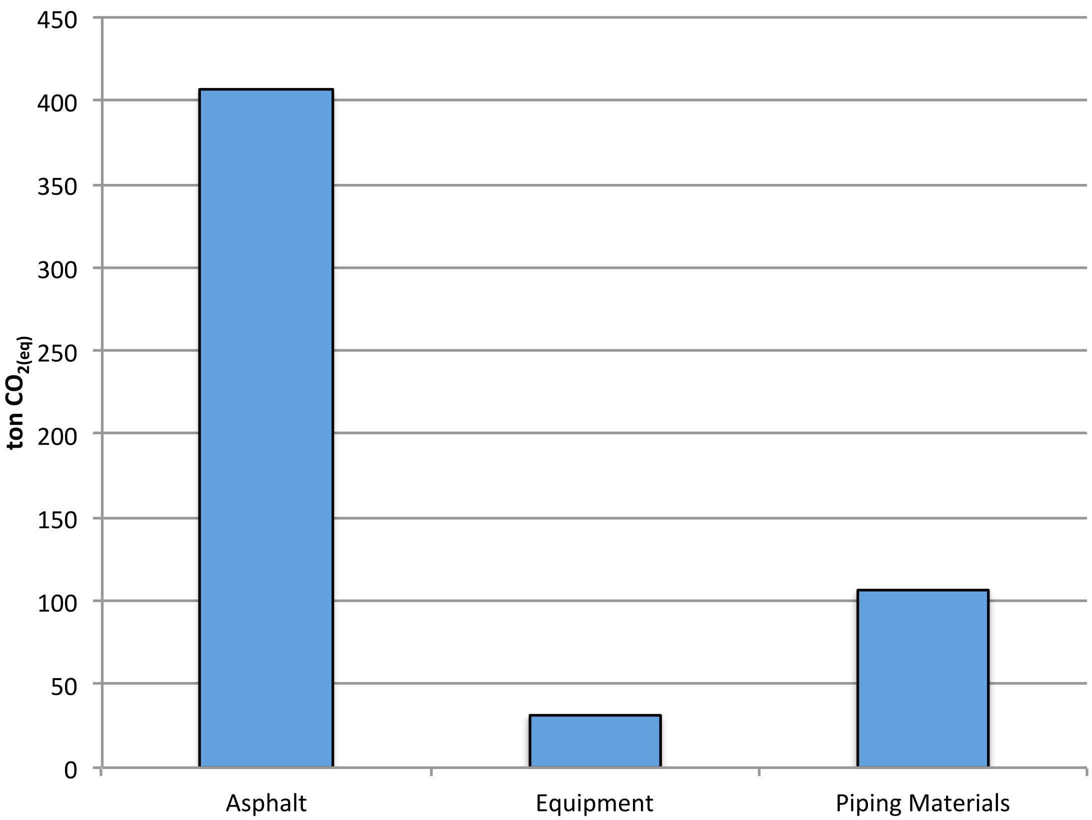

Figure 10. GHG emissions for annual maintenance outputs for the case study utility.

The majority of these impacts are from asphalt materials (56%) and pipes (38%), with construction equipment playing a small role (6%). Asphalt impacts could be significantly reduced by using horizontal directional drilling (HDD) construction methods, which will be detailed in the breakeven analysis section. Replacing traditional open-trench methods with HDD or other non-invasive pipe replacement is difficult for the case study utility because of significant external costs that are discussed in Chapter 8.

Pipeline construction impacts (2% of total emissions) are similar to the maintenance impacts, except that pipe materials are not included, and are not accrued annually. The initial construction of the entire case study utility's network was performed using open-trench techniques. The case study utility is experimenting with non-invasive construction techniques, but has not wholly adopted them.

Tank materials, as shown in Figure 6 and Table 18 (GHG footprint figure/table), include all water storage facilities GHG emissions. These facilities represent a small portion of the total utility emissions (1%). Concrete reservoirs, used often when aesthetics are a concern, compose 84% (8.2 million gal (31.0 ML)) of the total water storage capacity of the case study utility. This storage capacity was spread across 11 different reservoirs. Figure 11 and Table 19 detail the specific emissions resulting from concrete reservoir use.

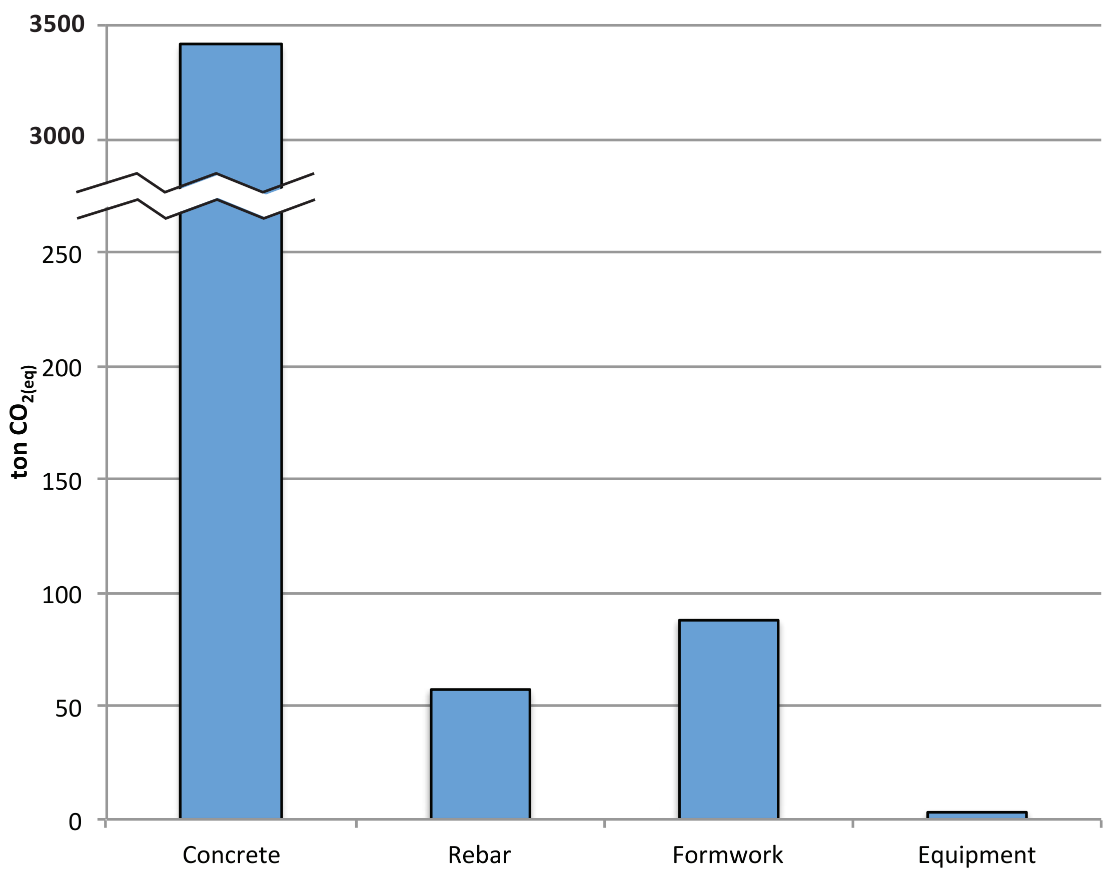

Figure 11. LCI GHG emissions for concrete reservoirs.

Material/ Input	**$CO_{2(eq)}$ (ton)**	**% of Total**	**$CO_{2(eq)}$ g/gal capacity**
Concrete	3412.5	83.70%	415.9
Rebar	573.0	14.05%	69.8
Formwork	88.1	2.16%	10.7
Equipment	3.4	0.08%	0.4
TOTAL	4077	100%	497

Table 19. LCI GHG emissions for concrete reservoirs.

For concrete reservoirs, volumes for concrete used varied based on each facility's radius based on the volume of capacity. Concrete used in the roof and foundation of the reservoirs varied based on the surface area. The thickness of the roof and foundation was assumed to be fixed. The reservoir walls' concrete varied linearly based on the circumference, and the height was assumed to be fixed for all capacities. Concrete used in the support columns varied linearly with capacity, and the catch basin inputs were assumed to be fixed for all facilities. Rebar, formwork, and construction equipment use were calculated on a per-gallon basis for the as-builts provided by the case study utility and scaled up to the different capacities. The total life-cycle GHGs emitted by reservoirs in the case study utility were dominated by concrete (84% of total emissions). Rebar contributed significantly (14%), while formwork (2%) and equipment use (0.1%) had minor contributions. Total concrete GHG emissions for reservoirs came mostly from the foundation (44%), walls (33%), and roof (21%). The columns and catch basin were negligible (0.7% and 0.2%, respectively).

Steel tanks make up 16% (1.6 million gal (6.1 ML)) of the case study utility's total storage capacity, which included 10 different facilities. Steel tanks are preferred by the utility over concrete reservoirs, but not always possible to build for aesthetic reasons. Figure 12 and Table 20 show the details for GHG emissions resulting from steel tanks.

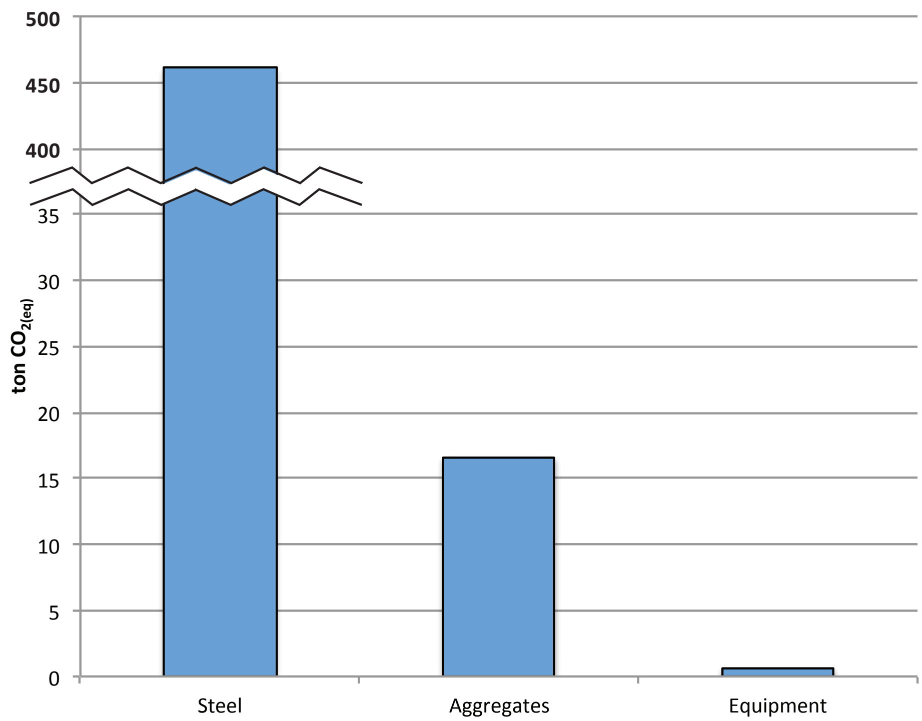

Figure 12. LCI GHG emissions for steel tanks.

Material/ Input	**$CO_{2(eq)}$ (ton)**	**% of Total**	**g $CO_{2(eq)}$ /gal capacity**
Steel	230.5	93%	28.1
Aggregates	16.6	7%	2.0
Equipment	0.6	0.3%	0.1
TOTAL	248	100%	30

Table 20. LCI GHG emissions for steel tanks.

Steel tanks were scaled up to the different capacities in a similar manner as concrete reservoirs. The tanks were all cylindrical in shape, so the radius for each tank varied based on the volume. Steel sheeting, which made up 93% of the total GHG emissions from tanks in the case study utility, was calculated separately based on the surface areas of the walls and caps (i.e., roof and base). The walls' surface area scaled linearly based on the circumference and height, where the radius increased but the height was assumed to be constant for all capacities. The caps' surface area varied with square of the radius. The walls accounted for 33% of the total steel GHGs for tanks, while the caps contributed 67%. The aggregates for tanks represented 7% of the remaining GHG emissions for tanks. The thickness for aggregates remained fixed for all tanks, and the volume of aggregates used varied on the tank radius and surface area of the tank base. Construction equipment represented a negligible fraction of the total GHGs (less than 0.1%), and was scaled linearly based on the emissions calculated for the tank as-builts provided by the case study utility.

As steel is the major material input into the tank facilities, it is expected that it will be associated with the greatest GHG emissions. Aggregates (crushed rock, pea gravel) are used as a foundation for the tanks and act as a barrier to prevent corrosion, but should be minimized whenever possible if GHG emissions from water storage ever become a concern for the case study utility. However, water storage is still only a very small portion of the overall GHG footprint and should not be targeted over other savings opportunities. The potential GHG savings in water storage and other WDS elements with comparatively small impacts could be very expensive in terms of economic costs.

Concrete reservoirs are selected in the case that aesthetics are an important design criteria, as they can be buried underground without risking corrosion. Concrete reservoirs have significantly higher emissions than steel tanks on a per-volume basis (497 g $CO_{2(eq)}$/gal and 30.2 g $CO_{2(eq)}$/gal respectively). Still, water storage only accounts for a very small portion of the total utility footprint (less than 1% in Figure 6). These storage facilities assessed in this research do not represent the only common design used by U.S. WDSs. Other designs, such as spheroidal tanks, are often used in place of the designs studied here.

With groundwater being the only source for the case study utility, wells play a vital role in the infrastructure system. However, the actual material and construction inputs of a well facility only account for 0.3% of the total GHG footprint. Figure 13 details the emissions of all the wells constructed by the case study utility.

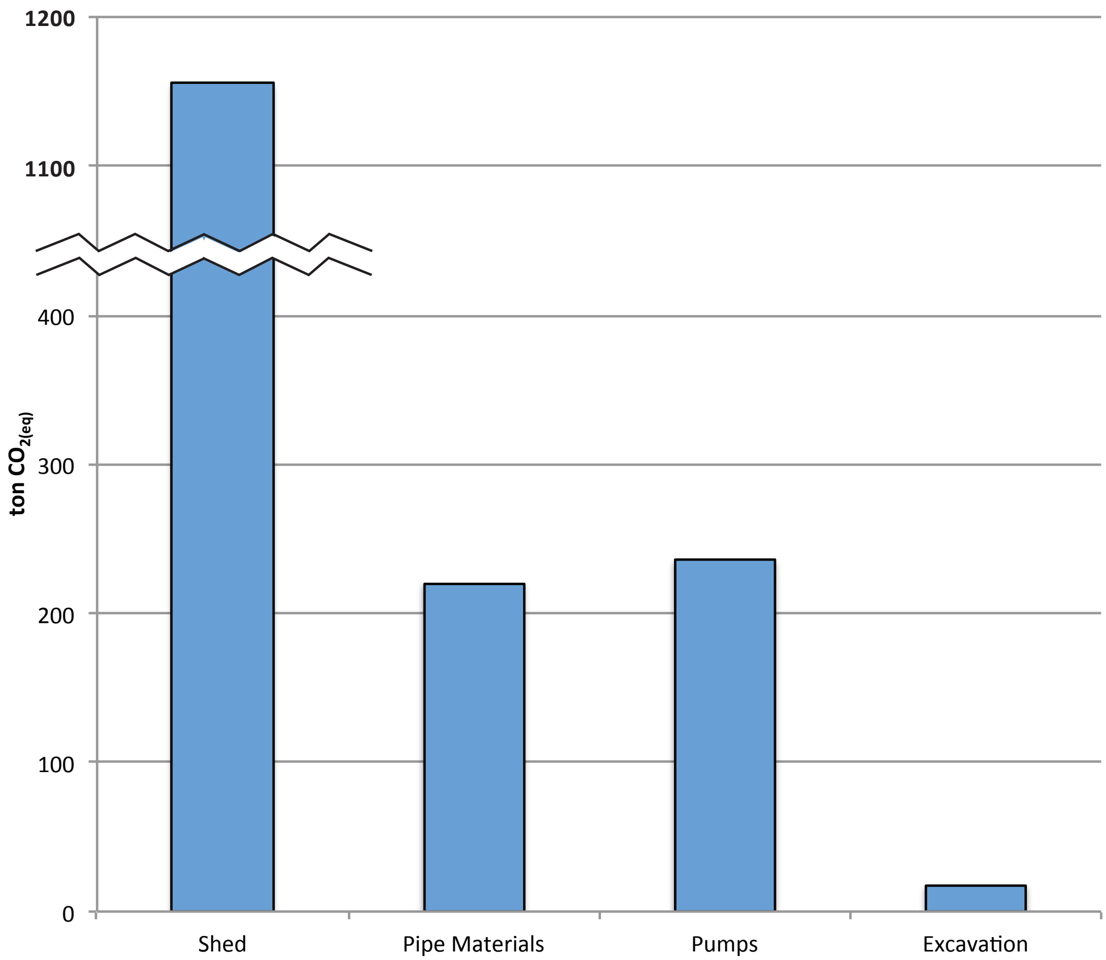

Figure 13. GHG emissions from well facilities.

The concrete and rebar inputs into the shed (which includes the foundation and any construction inputs) make up the majority of the GHG emissions (70% of total well emissions). Pipe materials represent the materials used in the column (steel) and casing (PVC) that draw water from the aquifer. Excavation represents any equipment used in drilling the well.

Booster pumps are used commonly throughout the case study utility's system to transport water to storage facilities at higher elevations to create a gravity-fed system. Similar to water wells, the material and construction inputs into these facilities compose little of the total utility footprint (0.2%). As described in the LCI, the booster pumps facilities are made up by a shed, which is similar to the shed used for wells, and usually multiple pumps. For all of the case utilities booster pump facilities, the sheds are 64% (757 ton $CO_{2(eq)}$) of the total emissions, and pumps are 36% (318 ton $CO_{2(eq)}$).

5.11 Growth Projections

The case study utility has experienced steady customer growth in the past decades, and projections for expansion are a continual part of planning. These projections were incorporated into this research by employing the same methods as the utility to determine how growth affected GHG emissions. Demand (total volume delivered) and pumping energy were assumed to grow exponentially at a rate of 2.0% for the next 20 years, starting in 2009, which represented the latest year of demand data provided by the case study utility. Projections for changes in the local electric utility's mix were then applied to the new pumping energy demands.

Emissions were calculated by projecting the possible electricity mix for future years. WDSs seeking to reduce their GHG footprint will benefit from electricity decarbonization. In 2012 the EPA created the first proposal for setting GHG restrictions on new power plant construction.[87] It is expected that over time utilities currently buying power from coal-intensive mixes (as in this case study) will have access to less coal intensive mixes or GHG emissions will be reduced through carbon capture processes.

Several cases were created for the potential electricity mix of the local electric utility for future years. The business as usual (BAU) case assumes that no changes will be made in the electricity mix. The local electricity mix, as discussed in the Chapter 5, is mainly composed of coal (60.5%) and hydropower (33.3%). There are two decarbonization scenarios based on the infusion of renewable energy (photovoltaic, geothermal, wind, waste). Case 1 uses historical data for the rate of increase of renewables in the national average mix over the last several years (2006-2010) to predict the electricity mix for the analysis period.[88] Case 2 uses the same projections as Case 1 for photovoltaics, geothermal, and waste energy, but assumes that all fossil fuels are phased out by year 20. The electricity supplied by these fossil fuels is replaced with wind energy. These same scenarios are analyzed again with the added assumption that the case study utility only experiences 5% losses in distribution instead of the 40% currently experienced. Table 21 shows the details for demand, pumping energy, and GHG emissions. These results are graphed in Figure 14.

			Case study utility Current Losses Scenarios			5% Losses Scenarios		
Year	**Demand (MG)**	**Pumping Energy (MWh)**	**GHGs (ton $CO_{2(eq)}$) BAU**	**GHGs (ton $CO_{2(eq)}$) Case 1**	**GHGs (ton $CO_{2(eq)}$) Case 2**	**GHGs (ton $CO_{2(eq)}$) BAU**	**GHGs (ton $CO_{2(eq)}$) Case 1**	**GHGs (ton $CO_{2(eq)}$) Case 2**
2009	9118	13831	10,269	9,181	9,178	6,675	5,968	5,966
2014	10076	15286	11,349	9,473	7,667	7,377	6,157	4,984
2019	11136	16893	12,543	9,619	5,736	8,153	6,252	3,729
2024	12307	18670	13,862	9,024	3,316	9,010	5,866	2,155
2029	13602	20633	15,320	6,932	326.0	9,958	4,506	212

Table 21. Results for projection scenarios for the case study utility.

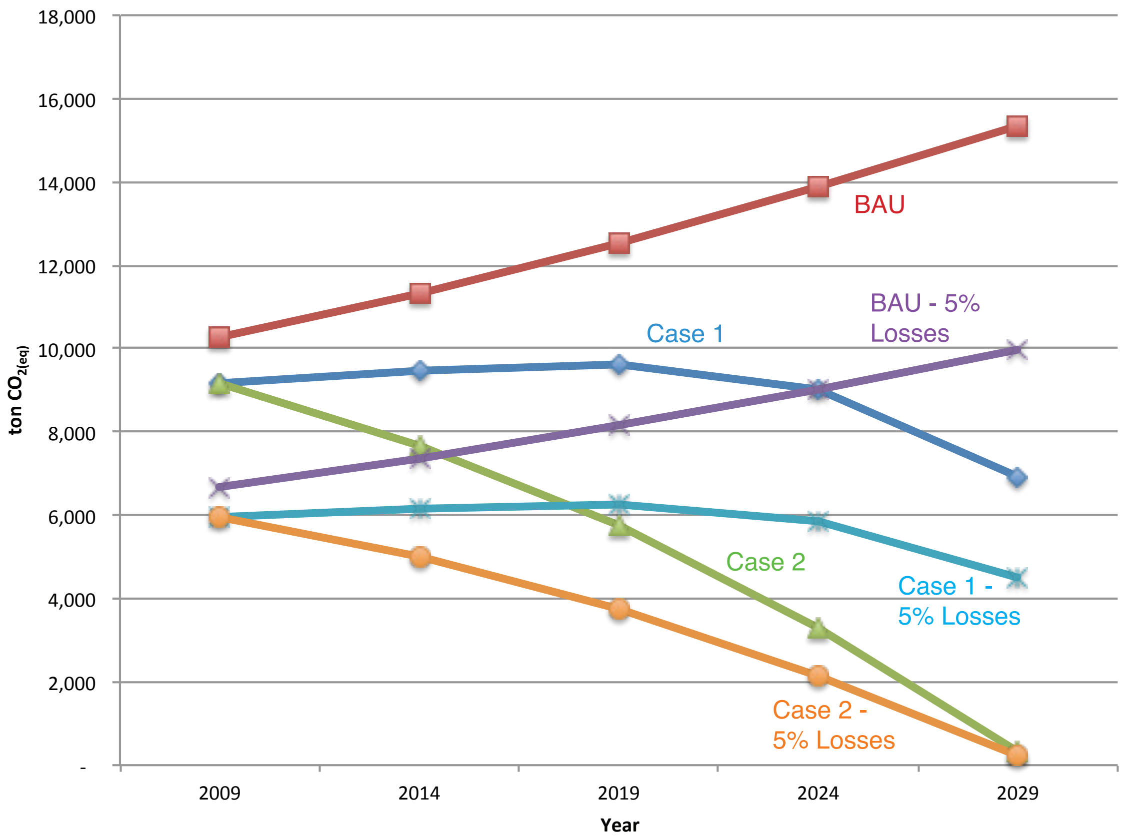

Figure 14. Projections for GHG emissions from demand growth for the case study utility.

These projections focus on reducing GHGs from pumping energy, the overwhelming contributor to the case study utility's GHG footprint. The results reveal that reducing the carbon intensity of the local electric utility can lead to substantial GHG reductions even in the face of sustained service growth. Reducing distribution losses again shows significant reductions by avoiding wasted pumping energy. Finding some combination of these two reduction options reveal, at least for the case study utility, the greatest opportunities for avoiding GHG emissions. Case 2 most likely is based on an overly optimistic growth projection of wind power (64% in 2029). Case 1 may be an attainable rate of renewable energy inclusion.

These projections use renewable energy as a means of reducing the carbon intensity of electricity mixes, but other methods could be used. Carbon capture and storage technologies for fossil fuels could be another means of reducing emissions from electricity production. This option could be a simpler transition for the case study utility's electricity supplier, which is heavily dependent on fossil fuels. Incorporating renewables may require a restructuring of electricity infrastructure due to intermittence of supply and the current peak loads of demand.

6. Greenhouse-gas Emission Reduction Tool for Utilities

6.1 Breakeven Analysis

For the case study utility, understanding leaks in the context of carbon emissions is a priority. The case study utility representatives proposed that the author find this relationship for an isolated length of pipe. In response, this dissertation includes a breakeven analysis tool that allows the user to vary inputs to determine the point where accrued GHG emissions from leaks matches the emissions from construction inputs.

The user can vary the pipe length, size, material, flow rate, pressure demand, leak increase rate (% increase/yr), elevation head, construction method, and electricity mix. The total head represents the embedded energy in the water flowing through the pipe segment:

$$h_{tot} = \frac{p}{\rho g} + z + \frac{v^2}{2g} + h_f$$

where *p* represents the pressure demand, ρ the density of water, g gravity, z the elevation head, *v* the flow rate, and h_f the head losses.[15] Head losses were calculated using the Hazen-Williams equation:

$$h_f = 10.67 \frac{Q^{1.85}}{C^{1.85} D^{4.87}} L$$

where *Q* represents the flow rate (m^3/s), *C* the friction coefficient (unitless), *D* the diameter (m), and *L* the pipe length (m).[15] The increasing head losses over time were modeled using a roughness growth rate of .025 mm/yr.[89] Hazen-Williams friction coefficients for the pipes available for analysis in the breakeven tool are listed in Table 22.

Material	Friction Coefficient
Cast-Iron	130
Concrete	120
Ductile Iron	140
DICL	120
PVC	150
Steel	145
PE	150

Table 22. Hazen-Williams friction coefficients for pipes analyzed. Source: (90).

Leaks for the isolated length of pipe were assumed to increase linearly based on the given leak increase rate. The embedded GHG emissions of the leaks were totaled over the user-defined analysis period using the following equation:

$$E_{lost} = \int_0^{t_f} E_i r t_f \, dt$$

where E_{lost} is the accrued emissions from leaks, E_i is the initial sum of embodied emissions, r the leak increase rate, and t_f the analysis period. GHG emissions are based on the embodied energy and electricity mix as defined by the user. Current options for electricity mixes are the local electric mix of the case study utility, the U.S. average, California, Texas and the 10 North American Electric Reliability Corporation (NERC) Regions.[75] Accrued head losses are also included as the pipe material degrades over the analysis period.

Construction inputs are defined by the user by selecting either open-trench or HDD methods. Open-trench calculations remain the same as the LCI analysis, and HDD construction method and equipment use were taken from a previous study.[46] HDD asphalt inputs were limited to a 120 ft^2 area (5.57 m^2) based on input from the utility studied. Although other, less invasive alternatives exist to reducing leaks, such as pressure management, the tool was geared to basing leak reduction solely on pipe replacement.

6.2 Sample Tool Results

Leak Increase Rate (%/yr)	Construction Method	Accrued ton $CO_{2(eq)}$ lost (Year 20)	$CO_{2(eq)}$ Breakeven Year
0.01	Open-trench	731.01	10.7
0.05	Open-trench	3,579.9	7.22
0.1	Open-trench	7,141.0	6.08
0.5	Open-trench	35,630	4.07
1	Open-trench	71,240	3.43
2.5	Open-trench	178,070	2.73
0.01	HDD	731.01	8.31
0.05	HDD	3,579.9	5.62
0.1	HDD	7,141.0	4.74
0.5	HDD	35,630	3.18
1	HDD	71,240	2.67
2.5	HDD	178,070	2.13

Table 23. Sample breakeven analysis results.

Table 23 displays sample results from running different scenarios within the breakeven tool. The electricity mix is based on the case study utility's local electricity mix, which is discussed in further detail in the LCI (Chapter 5). The

$CO_{2(eq)}$ breakeven year represents the year when accrued emissions from water losses match replacement emissions, which includes construction, material, and shipping emissions. Many of the inputs stay fixed for these scenarios. Flow rate was fixed at 500 gal/min (0.032 m^3/s), pressure demand was 40 psi (27,600 N/m^2), pipe length was 100 m (328 ft), pipe material was concrete-lined ductile iron (DICL), pipe diameter was 250 mm (10 in), and elevation head was 50 ft (15.2 m).

The fixed inputs were chosen because they represented either a lower bound or average of the utility studied. Flow rates and pressure demand represented a lower bound, while elevation head was the average pumping depth for wells. Pipe length represented roughly one street block of service connections. The pipe size was large enough that head losses were not substantial, meaning the vast majority of accrued emissions were a result of leaks.

6.3 Results Discussion

This tool provides drinking water utility decision makers with a method for evaluating pipe replacement scheduling based on GHG emissions. The different variables and input options allow the user to customize the analysis for a wide range of potential situations: varying head inputs, environmental conditions that lead to leaks, pipe materials, and electricity mixes.

If carbon emissions or energy were the only criteria in deciding when to replace piping, replacement would occur at intervals less than ten years, even with very low leak increase rates (0.01-0.05 %/yr). A more realistic leak increase rate for the case study utility would be 0.5-0.8 %/yr, which would suggest a replacement rate of about 4 years using open-trench construction.

Although the breakeven year is not significantly affected, using HDD construction methods in the place of open-trench reduces energy and emissions by over 50%, as use of asphalt materials is greatly reduced.

The case study utility operates on a 300-year pipe replacement schedule, which the utility believes to be common among U.S. WDSs because of the high economic and societal costs of replacing pipe. This pipe replacement schedule represents a reactive maintenance strategy where pipes are only replaced upon failure, as no pipes are expected to be in use for 300 years. The results of the breakeven analysis are in stark contrast to the case study utility’s replacement schedule, as these results only reflect an environmental replacement perspective. More context is needed for WDS representatives to make better use of the results from the breakeven analysis tool, which is presented in the next section.

7. Efficiency in Greenhouse-gas Emission Reduction Solutions

7.1 Emission Reduction Efficiency in Pipe Replacement

As discussed in LCI results, the utility experiences a high level of water loss in distribution (40% of total volume). This number is similar to other urban utilities that experience high losses from leaks. The Philadelphia Water Department, for instance, experiences 31% losses in distribution, and the Cleveland Division of Water loses 29%.[11] For reference, California's East Bay Municipal Utility District (EBMUD) has 7% losses in distribution,[12] and California averages 10% for all utilities.[91] Texas, currently experiencing the worst drought in its recorded history, averages 13% losses in municipalities.[10] A significant investment in operational costs to reduce leak losses is necessary, but it is cost effective in regions where water is more scarce. However, these investments can be viewed from a different perspective when incorporating GHG emissions into the overall decision making.

Based on the case study utility's estimated replacement economic cost of piping and results of the breakeven tool, the economic cost of reducing leaks can be compared to the associated GHG emissions. This comparison allows utilities to combine two objectives, minimizing both replacement costs and GHG emissions, into a single analysis when viewing pipe replacement schedule or leak reduction options. This analysis assumes the electricity mix and construction methods utilized by the case study utility are being used. Figure 15 shows the results of a comparison of the two objectives.

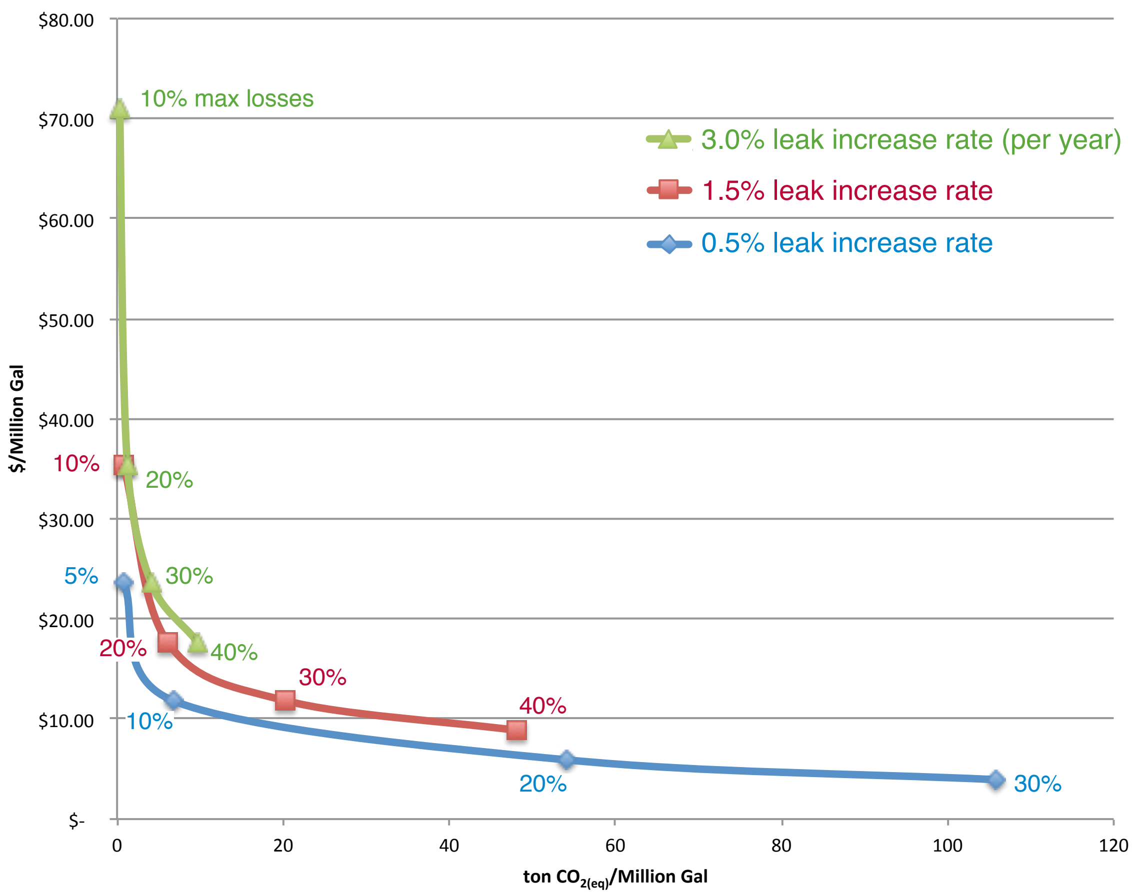

Figure 15. Leak reduction options for assessing pipe replacement scheduling based on different leak rate increases.

The different curves in Figure 15 are characterized by leak rate increases (%/yr), and the alternatives along the curves are maximum acceptable leak rates options. Axis units are per total volume supplied.

Determining exactly how each pipe in a WDS will increase in water lost to leaks over time is difficult, and no prediction model exists in the literature. Severable variables can affect a pipe's leak rate increase: soil conditions, water quality, pressure fluctuations, pipe size, and pipe material. The three different leak increase rates presented in this graph could represent three different pipes, and each point on the curves represents a utility's maximum allowable leak rate for each pipe. For Figure 15, the three pipes, represented by the three curves, have all the same characteristics for everything except leak increase rate: length, size, material, construction method, electricity mix, consumption flow, pressure, and elevation head. The specific inputs for these variables were the same as in Section 6.2.

The leak increase rate and maximum allowable leak rate will determine the replacement rate of the pipe. The pipe must be replaced when the maximum allowable leak rate is achieved, and this replacement rate iterates over the 50-

year analysis period. The accrued GHG emissions from water lost in leaks and pipe replacement inputs, from the breakeven tool, determine the total GHGs emitted. The economic costs are a reflection of the replacement costs over the analysis period. In this analysis, the case study utility's value of $1 million per mile (1.6 km) of pipe is used.

Figure 15 allows a utility to quickly determine the cost effectiveness of adopting a different leak rate for a pipe. For example, the case study utility, which operates around a 0.5% leak increase rate and a 40% leak rate, will find that achieving some leak rates, such as 20% or 30%, are more cost effective for reducing GHG emissions than very low leak rates (10% or 5%). These tradeoffs are further discussed in Section 7.2. The 40% maximum leak rate option for the 0.5% leak increase rate is not displayed on the graph to give clarity to the lower leak rates and different leak increase rates.

Similar the LCI results (Figure 6), the total GHG emissions in this analysis are dominated by the accrued emissions from leaks. These emissions will vary based on the electricity mix selected in the breakeven tool.

The analysis period used here is 50 years. Emissions accrued from leaks and head losses are capped at the analysis period length, and emissions from replacement are not included for maximum leak rates that have replacement rates longer than the analysis period. However, economic costs from replacement are still included as it is assumed that some maintenance inputs, such as emergency repairs, will still be necessary.

Only including the economic costs of replacement in the analysis ignores the costs of treatment and electricity purchases for pumping. These costs are embedded in the drinking water delivered to customers and lost in distribution. If these costs are included, only very low leak rates are tolerable. However, these extremely low leak rates are not sustainable. Chapter 8 discusses the societal costs that prohibit maintaining such low leak rates.

The curves are skewed towards the upper left quadrant of the chart as the leak increase rate grows larger. As discussed previously, 0.5 to 0.8%/yr are realistic leak increase rates for the utility studied, but other WDSs may have more corrosive water sources, different soil properties, or may operate at higher pressures resulting in higher leak increase rates. Higher leak increase rates force a shorter pipe replacement schedule when using the tool, which then result in fewer GHG emissions because accrued emissions from leaks are stymied. A shorter replacement schedule results in higher economic costs, pushing the curves further up the y-axis as leak increase rates grow higher.

7.2 Carbon Abatement Costs

The leak reduction analysis results can be placed in a wider context by calculating the carbon abatement costs (CACs) of sample leak reduction options. Emission abatement costs are used to compare emission reduction alternatives.[92] Table 24 shows the cost per metric ton of $CO_{2(eq)}$ for several leak reduction options for the case utility. These leak rates are assumed to be distribution losses resulting from leaks, which can be controlled through pipe replacement. Distribution losses beyond leaks, such as metering errors, unauthorized consumption, and background losses, are not included in the CACs.

Leak Rate Change Option	Cost Incurred ($/MG)	Avoided GHGs (ton $CO_{2(eq)}$/MG)	Carbon Abatement Cost ($/ton $CO_{2(eq)}$)
40% to 5%	$20.69	105	$0.20
40% to 10%	$8.87	99	$0.09
40% to 20%	$2.96	51	$0.06
30% to 5%	$19.70	105	$0.19
30% to 10%	$7.88	99	$0.08
20% to 5%	$17.73	53	$0.33
20% to 10%	$5.91	47	$0.12

Table 24. Carbon abatement costs for different leak rate change options for the case utility. MG denotes million gallons.

Based on pipe replacement costs of $1 million per mile, reducing leaks is a relatively cheap GHG emission reduction option. This result holds true even when targeting very low leak rates, such as 5%. Total U.S. CO_2 emissions from energy-related sources totaled 5.5 billion metric tons in 2011.[93] To offset a meaningful amount through leak reduction, for example, 1 million tons of $CO_{2(eq)}$, would cost between $60,000 and $330,000. As a reference point, a recent study revealed that switching to electricity from photovoltaic sources in place of natural gas sources would result in a CAC of $200 million per million ton CO_2.[94]

7.3 Pipe Material Selection

The case study utility uses mostly DICL in new pipe installations as the performance of the material is preferred. Other materials, such as plastic piping, which is often used in other WDSs, perform poorly under the significant variations in pressure that the case study utility experiences. Ductile iron piping has significantly higher strength (tensile, compression, yield) than plastic piping materials (PVC, PE), but plastic materials experience much less corrosion over the product lifetime.[11] There are still six different pipe materials used in the LCA of the case study utility's distribution network that have been quantified for GHG emissions in this dissertation. Although the case study utility focuses on installing only one, many of the other materials assessed in this work (reinforced concrete, PVC, PE) are commonly found in other U.S. WDSs.[50]

The materials were assessed for both costs and GHG emissions for a 50-year timeline in the same fashion as the leak reduction options. The costs included the pipe material costs (see Tables 6-11) and costs of replacement ($1 million per mile). GHG emissions were based on pipe materials, replacement inputs, head losses, and leaks. Replacement inputs were calculated in the same way as pipe maintenance for the LCI and breakeven analyses. Replacement rate was determined from the number of expected pipe bursts over the analysis period. The number of pipe bursts was determined from the following equation:

$$N(t) = N(t_0)e^{A(t-t_0)}$$

Where *N(t)* is the expected number of breaks per-unit-length, *N(t_o)* the breaks per length in the installation year (t_o), and *A* the growth rate factors.[95] The growth rate factor was estimated from existing growth rate factors and the case study utility's ranking of the different materials' durability.[96] GHG emissions from leaks and head losses were calculated using the breakeven tool, and leak increase rates were estimated for each material based on the utility's durability rankings. Table 25 shows the total costs and GHGs calculated from this analysis.

Material	**Pipe Bursting Growth Rate**	**Expected Pipe Bursts**	**Leak Increase Rate (%/yr)**	**Accrued Head and Leak GHGs (kg $CO_{2(eq)}$/m)**	**Total Costs ($/m)**	**Total GHGs (ton $CO_{2(eq)}$/ m)**
Concrete	0.06	3	0.75	2.12E+09	$985	2.12E+06
DICL	0.02	1	0.5	1.41E+09	$378	1.41E+06
Cast Iron	0.04	1	0.6	1.70E+09	$378	1.70E+06
Steel	0.06	3	0.7	1.98E+09	$1,016	1.98E+06
PVC	0.1	18	0.8	2.26E+09	$5,921	2.26E+06
PE	0.1	18	0.81	2.29E+09	$5,773	2.29E+06

Table 25. Results for pipe material costs and GHGs in selection analysis.

The results, calculated over a 50-year period, are once again dominated by leaks. Head losses contribute very little to the overall combination of head losses and leak GHG emissions. The pipes with high replacement rates (PVC, PE) show greater replacement inputs, as the case study utility stated that these materials do not perform well under high variations in pressure. Still, the replacement outputs are negligible compared to the leak impacts. These results were assessed to determine if multiple efficient options for piping existed based on the analysis criteria of costs and GHG emissions. The different pipe materials were assessed using the same Pareto efficiency analysis that was described in Section 4.3, which is typically used in design problem studies. Using Pareto efficiency to assess different pipe options is a simple application of the methodology to identify the optimal material alternatives when both minimizing costs and GHG emissions are objectives. Figure 16 shows the Pareto results of the different piping materials assessed in this dissertation.

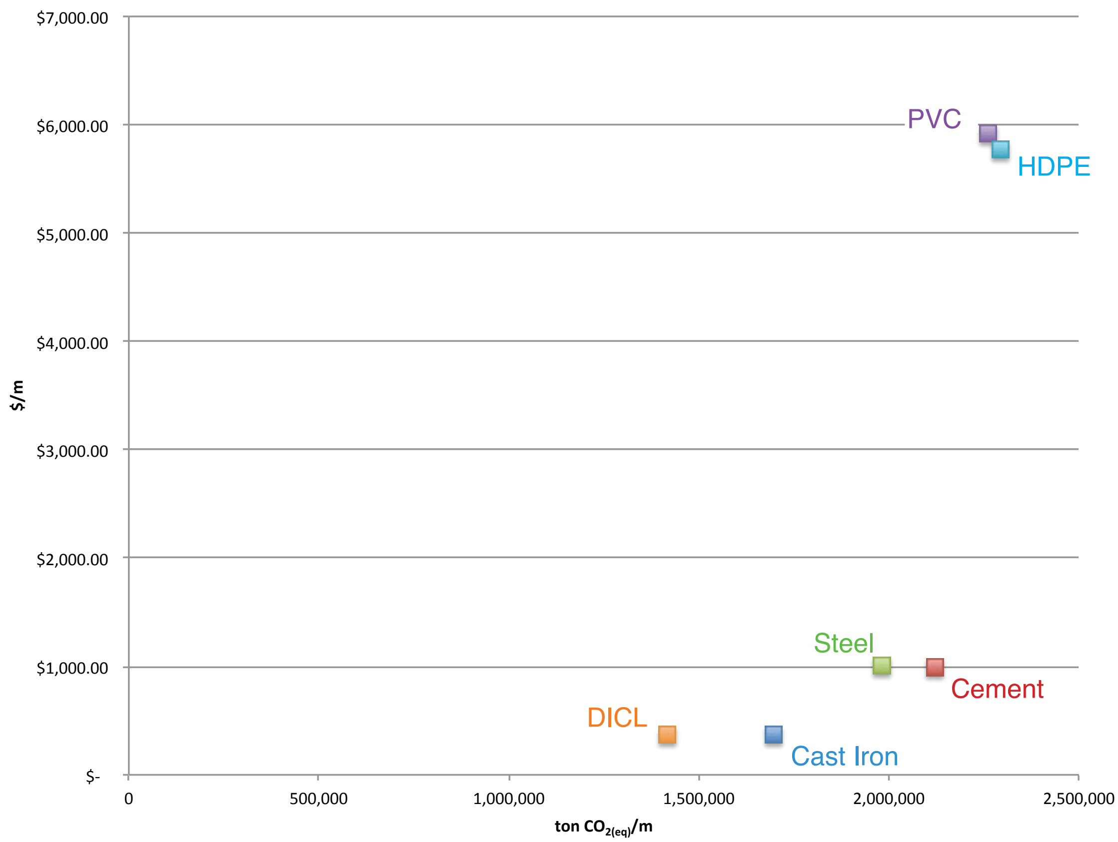

Figure 16. Pareto efficiency analysis for piping materials.

However, Figure 16 reveals that no Pareto fronts could be identified as only DICL is an efficient option. It should be noted again that the durability of the materials (break growth rate, leak rate) were estimated from the case study utility's feedback and not actually based on a numerically derived relationship. The durability performance of these materials could perform very differently for a WDS with different hydraulic characteristics than the case study utility. Based on a new set of durability rankings, Pareto fronts may exist when selecting pipe materials.

8. Research Synthesis

8.1 Regional Greenhouse-gas Emission Reduction Scenarios

Global warming-related policies being considered or already in place are forcing U.S. industries to reconsider traditional business practices. Some states have already implemented such policies. For example, California has decided that the 1990 GHG emission level will serve as the cap for 2020 emissions.[97] WDSs do not immediately come to mind when discussing GHG reduction policies, where power plants and other manufacturing facilities are the large targets. However, as major consumers of electricity,[7,8] emissions from WDSs will be targeted as a significant source for GHG reduction.

In its 2008 scoping plan, the California Air Resources Board (CARB) estimated that almost 5 million tons of $CO_{2(eq)}$ could be saved by the state's water infrastructure, with over 40% of this number (2.0 million ton $CO_{2(eq)}$) coming from potential energy efficiency improvements.[97] Based on the findings of this research, it is possible that these projected savings from water efficiency improvements could be achieved only through leak reduction, assuming that the majority of leaks can be stemmed through pipe replacement. The case study utility's LCI results were combined with California-specific transmission, distribution, and treatment data to create GHG intensity estimates. Table 26 displays the different WDS elements contributing to three different estimates for California's GHG intensity of drinking water.

	Best Estimate		**High Estimate**		**Low Estimate**	
WDS Element	**g $CO_{2(eq)}$ /gal**	**% of Total**	**g $CO_{2(eq)}$ /gal**	**% of Total**	**g $CO_{2(eq)}$ /gal**	**% of Total**
Pumping Energy	2.05	82%	4.50	91%	1.13	71%
Piping Materials	0.07	2.7%	0.07	1.4%	0.07	4.3%
Tank Materials	0.01	0.6%	0.01	0.3%	0.01	0.9%
Well Materials	0.00	0.1%	0.00	0.1%	0.00	0.2%
Booster Pumps	0.00	0.1%	0.00	0.0%	0.00	0.1%
Pipe Construction	0.02	0.8%	0.02	0.4%	0.02	1.3%
Maintenance	0.02	0.6%	0.02	0.3%	0.02	1.0%
Treatment	0.33	13%	0.33	6.7%	0.33	21%
TOTAL	2.50	100%	4.96	100%	1.59	100%

Table 26. Three estimates for the GHG intensity of drinking water in California.

Quantities for delivered drinking water were taken from California's Department of Water Resources for 2005, where deliveries totaled almost 27 trillion gallons (100 TL).[98] Three general qualities of water were used for consumption by

California: freshwater, recycled, and desalinated.[98] LCA treatment GHG emission factors, specific to California case studies, were applied to each water source.[31] The pumping energy values were calculated from a CEC report that provided high and low energy intensities for transmission and distribution of drinking water.[99] The GHG intensities and percentage of water allocated from each source are detailed in Appendix B. Based on the water supply source, a different energy intensity was assigned: high, low, or average. Table 27 shows the energy intensities taken from *(99)*.

	Transmission (kWh/MG)	**Distribution (kWh/MG)**
High	14,000	1,200
Low	0	700
Average	7,000	950

Table 27. Energy intensities for transmission and distribution of water in California. Source: (99).

Whether the high, low, or average intensity was used varied by the different water source. The three different estimates each use a different combination of the energy intensities, resulting in GHG intensities for each source shown in Appendix B. For water sources such as the State Water Project, higher transmission values are used. Other sources, such as those destined for gravity-fed systems commonly found in Northern California, will have lower transmission and distribution values.[99] The energy intensities were applied to the California average electricity mix (55% natural gas, 17% nuclear, 13% hydropower, 6% geothermal, 3% wind, 3% biomass).[75] The pumping energy numbers were adjusted to reflect the 10% average water losses statewide,[91] whereas the treatment numbers already included losses. The final GHG intensity for each estimate was based on a weighted average of how much water was pumped from each source. The specific methodology used in applying the treatment and pumping energy numbers from the different reports for each water source are detailed in Appendix B.

From Chapter 7's results, one can assume that emissions from replacement are negligible compared to the accrued emissions from leaks. Knowing this, the annual emissions savings were calculated for reducing losses from 10%, which is the current statewide average,[91] to 5% assuming that these losses could be reduced through pipe replacement. Table 28 shows the results of this analysis.

	Best Estimate	High	Low
GHG savings (ton $CO_{2(eq)}$)	6,251,000	12,691,000	3,852,000
CAC ($/ton $CO_{2(eq)}$)	$1.89	$0.95	$2.97
Total $ (rounded)	$11,803,000	$12,108,000	$11,449,000

Table 28. CACs and total costs of GHG abatement for three California cases of reducing leaks from 10% to 5%.

The CACs are based on the accrued emissions from leaks over a 50-year analysis period and the case study utility's replacement cost estimate of $1 million per 1 mile of piping. This analysis assumes that leaks and demand are constant over this analysis period. The uncertainty associated with this assumption is discussed in Section 8.3. The GHG savings are based on the current estimated annual emissions from drinking water supply determined in this analysis. The costs in the CACs are based on the replacement rate determined by the breakeven tool for the given leak rates. Pipe replacement costs are assumed to not vary by geographic location.

For all three estimates in Table 28 the annual GHG savings exceed the 2 million ton $CO_{2(eq)}$ projected by CARB, but at a higher CAC than the case study utility (Table 24). This is due to the diminishing return on investment with reducing leaks, as displayed in Figure 15.

Texas is another state where water scarcity and a water-intensive economy create a strong focus on minimizing losses in WDSs. As discussed in Chapter 1, Texas currently loses 13% of water in distribution.[10] 2010 consumption of drinking water totaled over 4.5 trillion gallons (17 TL).[100] Three average GHG intensities for Texas were calculated based on the same data used for California. Texas has more fossil fuels in the state's average electricity mix than California or the case study utility (48% natural gas, 36% coal, 10% nuclear, 2% wind).[75] Water supply data for Texas only reported groundwater and surface water as sources, which were assumed to be freshwater sources.[100] The final Texas values differed from California based on assumptions for treatment, transmission and distribution, which are detailed in Appendix B. Table 29 displays the different WDS elements contributing to three different estimates for Texas's GHG intensity of drinking water.

	Best Estimate		High Estimate		Low Estimate	
WDS Element	**g $CO_{2(eq)}$ /gal**	**% of Total**	**g $CO_{2(eq)}$ /gal**	**% of Total**	**g $CO_{2(eq)}$ /gal**	**% of Total**
Pumping Energy	0.90	62%	4.46	89%	0.59	52%
Piping Materials	0.07	4.7%	0.07	1.4%	0.07	6.0%
Tank Materials	0.01	1.0%	0.01	0.3%	0.01	1.2%
Well Materials	0.00	0.2%	0.00	0.1%	0.00	0.3%
Booster Pumps	0.00	0.1%	0.00	0.0%	0.00	0.2%
Pipe Construction	0.02	1.4%	0.02	0.4%	0.02	1.8%
Maintenance	0.02	1.1%	0.02	0.3%	0.02	1.4%
Treatment	0.43	29%	0.43	8.5%	0.43	37%
TOTAL	1.45	100%	5.01	100%	1.14	100%

Table 29. Three estimates for the GHG intensity of drinking water in Texas.

The estimated costs and GHG savings of reducing leaks from 13% to both 10 and 5% were calculated using the GHG estimations of supply from Table 30.

	Best Estimate	**High**	**Low**
GHG savings (ton $CO_{2(eq)}$)	354,802	1,306,936	272,527
CAC ($/ton $CO_{2(eq)}$)	$1.25	$0.36	$1.59
Total $ (rounded)	$445,000	$474,000	$434,000

Table 30. CACs and total costs of GHG abatement for three Texas cases of reducing leaks from 13% to 10%.

In the Texas estimates, reducing leaks from 10% to 5% saw an increase in the CACs, as seen in Table 31. The increasing CACs associated with targeting low loss levels (less than 10%) are consistent across all scenarios assessed in this research.

	Best Estimate	High	Low
GHG Savings (ton $CO_{2(eq)}$)	922,125	3,396,705	708,294
CAC (\$/ton $CO_{2(eq)}$)	\$2.51	\$0.73	\$3.18
Total \$ (rounded)	\$2,312,000	\$2,466,000	\$2,253,000

Table 31. CACs and total costs of GHG abatement for three Texas cases of reducing leaks from 13% to 5%.

The GHG intensities of drinking water and CACs of the different regions analyzed in this dissertation are plotted together in Figure 17 to visualize the variations.

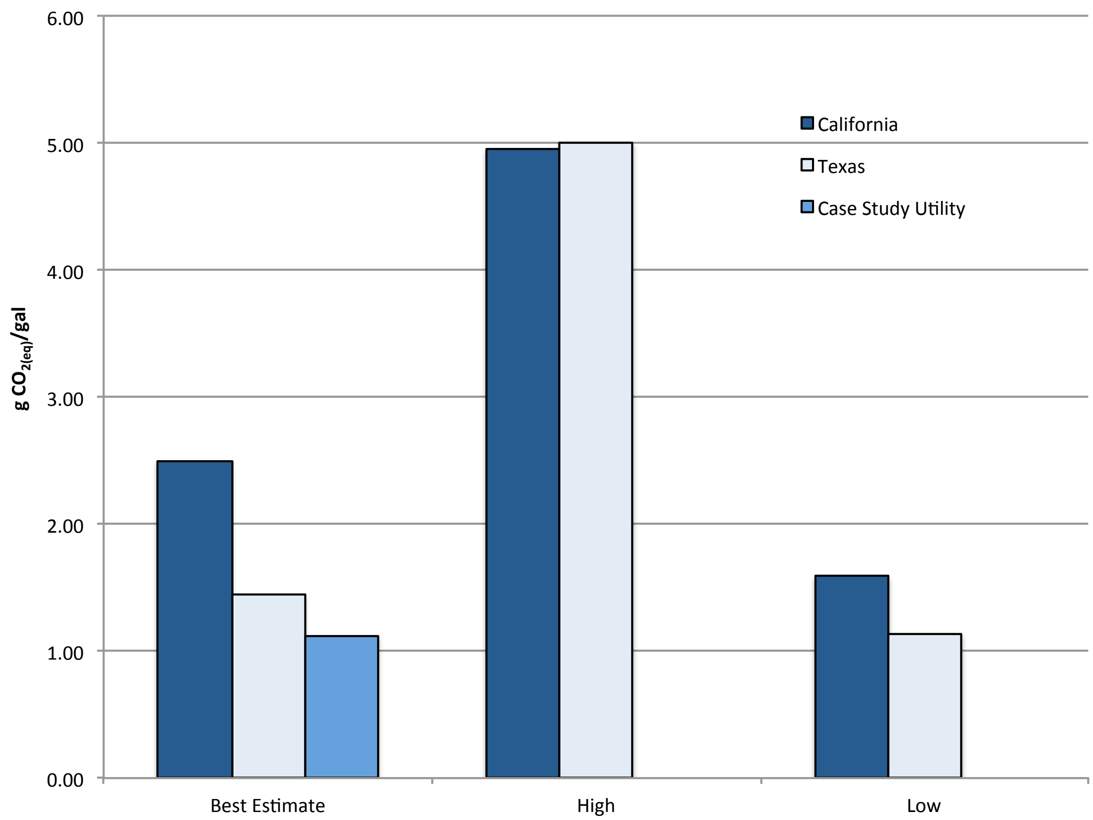

Figure 17. GHG intensities of drinking water for three different U.S. regions.

The best estimate results vary primarily on the associated transmission of water necessary for the different regions. For California, a large portion of the state, namely Southern California, depends on drinking water pumped over large distances from distant sources such as the Colorado River. This results in a higher GHG intensity despite having a very low loss rate. The case study utility requires no transmission as the end users are located directly over the water source. However, the case utility has distribution values, which are summarized by the total pumping energy used by the case study utility, that are similar to the maximum distribution values seen in California due to the substantial volume of losses the case study utility experiences. Electricity mixes also play an important role in the GHG intensities, which was made evident in the projections of the case study utility's GHG footprint. See Appendix A for full details on electricity mixes used for California and Texas.

Figure 18 reveals that regions or WDSs with substantial losses contain the greatest potential for cost-effective reduction of GHGs through leak reduction. However, even the regions that experience diminishing returns on investment in reducing GHGs through pipe replacement still have CACs two orders of magnitude less than installing residential photovoltaic systems.[94]

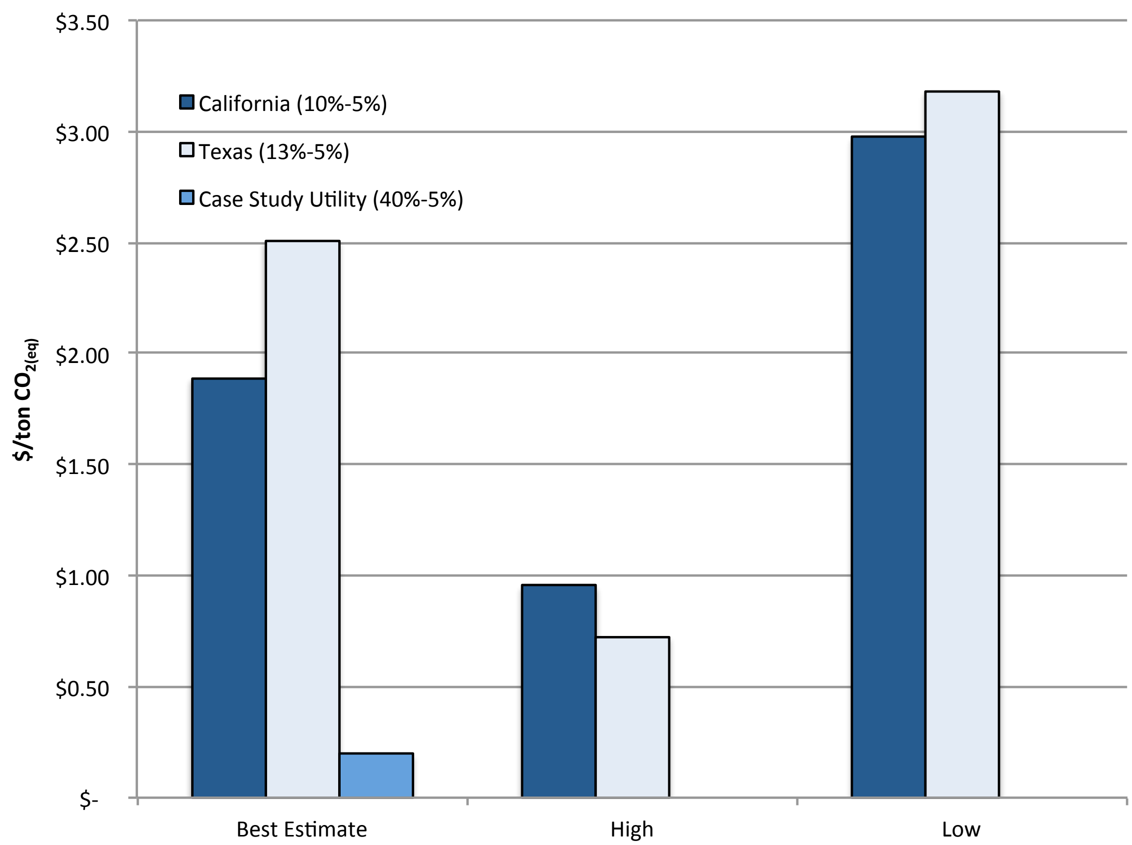

Figure 18. CACs of reducing losses to 5% of total drinking water supply for three different U.S. regions through pipe replacement.

As discussed in Chapter 5, utilities can vary considerably in design and operation. This is especially true of treatment and pumping inputs. The methods presented in this section reveal what can be inferred about a state or utility's GHG footprint and potential for savings by applying the best data available.

8.2 Policy Implications

Unlike some other products, water must be available at an acceptable quality and supply level for human survival. Water has an infinite benefit. This dissertation has shown that many opportunities exist for GHG emission savings that policy makers can incentivize or dictate without sacrificing service and with the added benefit of saving water resources. The previous section revealed scenarios, other than the case study utility's, where GHG emissions can be cost-effectively avoided through leak reduction. This opportunity represents the "lowest hanging fruit" for policy makers to target GHG emissions in WDSs while attaining the benefit of water resource protection.

If the costs of reducing leaks are prohibitive, legislators and utilities may have to explore water conservation as a means of reducing emissions in drinking water supply. This option will be difficult for states such as Texas and California, where the water intensive agriculture industry is a major contributor to the state economy. In circumstances such as these, greater spending on leak reduction and tapping new resources (desalination, recycling) may be acceptable options. Still, utility representatives and state legislators should explore the feasibility of imposing consumption restrictions. Increasing the price of water, either for all consumption or past a certain level, could help achieve conservation goals. Maintaining the same sector contributions of a water-intensive economy could temporarily be accomplished by employing conservation technologies such as drip irrigation that still allow for a similar agricultural output. However, if water demand continues to grow, a shift from relying on water-intensive economic sectors will be necessary for regions such as Texas.

As stated in Chapter 1, this research focuses on the environmental benefits of reducing real losses only, which usually dominate total distribution losses. Reducing apparent losses as well holds the same GHG reduction potential, but will come at different costs than pipe replacement. Finding sources of apparent losses can come through developing better metering technology and performing water audits.[13] Avoiding the compounding of embedded emissions in drinking water through loss reduction in distribution can only fully be achieved by targeting both real and apparent losses.

Another option for reducing the embedded emissions of drinking water, beyond leak control or resource conservation, is to curb the pumping energy inputs. The case study utility must maintain a pumping capacity that can match a fire flow requirement that is more than double the average daily demand of customers at all times, creating a higher pressure demand than is ordinarily necessary. This greatly increases the pumping energy inputs of the utility as the pressure head constitutes the majority of the total head at higher pressures (60 to 80 psi (414 KPa to 552 KPa)).

U.S. utilities cannot fall below this operating pressure as their insurance costs would rise significantly if the utility failed to meet fire flow requirements. High operating pressures can compound a utility's costs and GHG footprint past energy demand; flow rates through existing leaks are greater, and larger pressures are related to greater frequency in pipe breaks.[13] The case study utility stated that sections of their distribution system where pressure reducing valves (PRVs) are used experience fewer leaks. Fire flow requirements can be dictated by policies. The need for high-pressure water to fight fires could be alleviated with pumps installed on fire trucks. An optimal pressure can be found that meets the demands of customers while minimizing energy inputs.

8.3 Uncertainty Discussion

Many of the data sources presented in this study are new for research in this field. Previous research had often used the same data source, particularly for pipes.[36,38,42,46] The case study utility had a wide range of pipes in use that needed individual data sources for an accurate footprint presenting opportunities to seek out new, accurate sources. In the case of pipes, new LCA sources were used for steel, PVC, and PE pipes. The steel pipe data were based on European and global manufacturing data, but are representative of the same processes used in North America.[52] PVC and PE pipes were based on European processes, but it could be assumed that electricity was the major energy source in production.

Throughout the study, data were selected to reduce the use of EIO-LCA, widely applied in prior WDS LCA work.[25,40] EIO-LCA, although incorporating a comprehensive assessment of the upstream supply chain, has unavoidable uncertainties. The method uses aggregate data, thus specific products cannot be distinguished, and also uses U.S. averages which often do not reflect local characteristics. The process sources for concrete and asphalt allow for the local electricity mix to be employed in assessment, and the concrete data are specific to the design details used by the utility. The LCA data for plate steel, used in water tanks, are for North American production methods.[52]

In creating a GHG footprint, the utility provided their most accurate data sources whenever possible. Piping materials are an exact reflection of what the utility measures in their geographic information system. Pumping energy uses the total electricity purchases at each well and pump throughout the system, so the precise amount of electricity inputs are modeled. The impacts of each individual reservoir, tank, pump, and water well were found throughout the WDS. A site visit allowed for a greater understanding of the appropriate assumptions when necessary.

The regional scenarios for estimating GHG intensities of drinking water and CACs of leak reduction were not performed at the same level of detail as the case study utility, and therefore carry a higher level of uncertainty. Treatment values were based on LCA data from a study that used data directly from California utilities.[31] These treatment values were applied to the different water sources: desalinated, recycled, and freshwater.[99] Texas data only reported freshwater supplies.[100] As treatment values were only provided for case studies in California, specific treatment processes will vary between different utilities and water sources. This could change in the future as states such as Texas and California begin acquiring water from new sources that will require greater treatment inputs.

Transmission and distribution energy intensity values were California-specific, but limited to only maximum and minimum values.[99] The energy intensities were applied to the state average electricity mixes with LCA emission factors to create GHG intensities. High, low and average values were applied to the three different estimates. The estimates for how these intensities were applied to each water source or end-use type, as seen in Appendix B, were based on the researcher's best estimates. These estimates were supported by a general description of California's WDSs,[99] but no such report existed to support the Texas estimates. It was assumed that little transmission was currently necessary in Texas, but this could change significantly if local supplies cannot support the demand.

8.4 Future Work

This dissertation provides contributions to WDS LCA and sustainable solutions for drinking water utilities. Still, there are many areas that can be expanded upon that could not be accomplished within the scope of this research.

This work stops at GHG emissions because of incomplete data availability to quantify other environmental metrics. Much of the existing data sources only quantify GHG emissions and embodied energy, and often it is unclear what fuel or combustion method is being used and whether the energy source is primary or secondary, all of which are essential in tracking emissions beyond GHGs. Determining air emissions of EPA criteria pollutants and other common air pollutants would be the next step in assessing air emissions. These emissions of concern include NO_x, SO_x, CO, PM, VOCs, and O_3.

Air emissions only represent one category of environmental impacts commonly quantified in LCA. Other impact categories will prove to be highly relevant in different locations. For example, in areas where water quality problems will arise from leaks and structural damage to pipes, human health impacts will be of concern. WDSs requiring expansion will potentially need to construct new facilities and piping mains in new areas, where ecological damages and land use impacts may be of concern. Determining these kinds of impacts requires the implementation of LCIA, where results will be driven by a strong understanding of the local conditions in the LCA model.

The specific WDS elements presented in this dissertation are common or similar to most U.S. WDSs. However, drinking water utilities vary in material use and facility design. Pipe materials, where LCA data are still needed for materials that have yet to be assessed, such as vitrified clay pipe, pose a data challenge. Other pipe materials need more detailed LCA studies that vary based on diameters or are more specific to a given material. DICL and cast iron pipes are loosely assessed in EIO-LCA, as specific LCA data are still needed for these materials. Different facility designs exist that could affect a specific WDS element's GHG footprint. For water storage, this research is limited to steel and concrete cylindrical tanks. Artificial reservoirs too large to cover would require significantly larger construction and material inputs. Evaporation will play a role in impacts for designs such as these. Water wells are limited to open-ended designs. WDSs are beginning to employ perforated designs that could improve efficiency and reduce pumping energy.

The scenarios analyzed in Section 8.1 represent the potential this dissertation has for additional analyses at state and national levels, but data availability is limited. If data access to treatment, pumping energy and water losses in WDSs became more attainable, the LCA model presented in this research could be applied to more utilities and regions. With these data, a comprehensive and accurate understanding of the potential for GHG abatement could be developed for WDSs.

More opportunities exist to curb pumping energy demands exist than could be quantified in this work. One that had been discussed with the case study utility, but could not be assessed for lack of data, was the potential of using high-efficiency pumps or variable speed pumps to reduce loads. The economic costs of these pumps should also be determined to analyze the cost-efficiency of the environmental savings.

Water rights and pricing play a significant role in a WDS's current GHG footprint, and both stand to be important policy topics in water-scarce regions. For water rights, where local policies dictate how much of a certain water source a utility can access, a change in the allocation of water rights will force utilities to make infrastructure changes. A change could require using recycled water or seeking new water sources.

Water pricing could also change in regions with population growth and water scarcity. Higher pricing could lead to water conservation by customers, or use of lower quality water (e.g., greywater) that comes at a cheaper price for appropriate uses such as landscape irrigation. These dynamics in water policy are inherently linked to the GHGs of WDSs.

Eventually, a utility working to reduce its GHG footprint by targeting the main impact contributors identified in this research must be tracked to gauge the effectiveness of the recommendations made herein. The current body of work outlines the known barriers, but the recommendations for reducing emissions are based on estimates and projections. Each utility will experience different difficulties, but by observing a utility's efforts in achieving emission reduction goals, the major hurdles can be identified and a blueprint can be made for future utilities.

8.5 Recommendations

WDSs with similar circumstances as the case study utility should first target pumping energy and reducing leaks in addressing their own GHG footprint. Although the case study utility experiences a high volume of water losses to leaks and low treatment inputs, many U.S. utilities will find similarities in their own drinking water supply. Many portions of the United States rely on nearby freshwater sources and distribute through aging pipeline systems. Low treatment inputs are common for freshwater sources, even for water imported over long distances.[31]

The case study utility's substantial losses are aggravated by its history of annexing smaller distribution systems. Ideally, in a gravity fed system where water is pumped from the wells to tanks at higher elevations, there would be dedicated transmission mains, which do not exist in the case study utility. These mains would be larger and capable of accepting high-pressure water that must overcome the elevation differential. The high capital costs, both societal and economic, prevent the utility from this type of overhaul in design.

For the case study utility, all efforts for reducing their GHG footprint should be directed at finding methods to curb pumping energy impacts. Because of the sizeable losses in distribution, avoiding the embedded emissions from these leaks is the most cost-effective way of achieving reductions in pumping energy. Cutting losses by half still retains a loss rate notably higher than for other U.S. WDSs, but represents a significant savings in total GHG emission outputs (17%). If valuing this reduction by only replacement costs, it is highly cost effective. This level of savings could not be achieved in any other WDS aspect because of the dominance of pumping energy and leaks in the results.

As shown in the projections, reducing the carbon intensity of the local electricity mix used for pumping energy has a drastic effect on reducing total emissions. Although the existing options for reducing GHGs in the electricity mix are not as cost effective, a utility seeking to reduce GHG emissions could benefit greatly from promoting policies or public awareness for decarbonization. Funding renewable energy projects or constructing their own systems such as roof-mounted photovoltaics could accomplish this goal.

However the case study utility must cope with external costs that make leak reduction a difficult challenge. A cash infusion is not the only problem that must be overcome in implementing a leak reduction program of this magnitude. A sizeable work crew would have to be established, one that may be unsustainable for the utility and city as a whole. Assuming the bulk of the pipe replacement could only be done in warm weather, this work force could only be employed for roughly half the calendar year. Few skilled laborers will find this type of work schedule acceptable. The case study utility has run into similar problems when trying to find contractors to perform non-invasive pipe construction.

The case study utility must also accept the societal costs associated with a significant leak reduction effort. Service interruptions, altering traffic patterns (with increased congestion), and aesthetic effects all come with ramping up pipe replacement. The burden on the public could result in sizeable backlash that could hamper the utility's public image or ultimately change public policy to impeded the utility's leak reduction efforts. However, as a positive public relations benefit associated with leak reduction, the case study utility would be viewed as a good custodian of natural resources and could use this to bolster its public image.

The case study utility could minimize societal costs by spreading out construction over a longer period, so pipe replacements are staggered and a larger work crew can be sustained. Variations in work loads between warm and cold weather season could be minimized for the utility's workforce, and contractors outside the utility's work crews could be brought in for long periods of each year to supplement the work force for major projects. This type of effort would require a budget increase for the case utility, which is not feasible at this point, but may become possible if water scarcity or GHG emission reduction become important considerations.

These recommendations apply to the case study utility, but could be important to other WDSs with similar circumstances. More applicable are the LCA methods detailed in this dissertation for several components that are common amongst utilities and can easily be tailored for new inputs, such as water storage, piping materials, pumps, wells, and construction, where data are available. WDSs seeking to quantify their own GHG footprint should tailor this dissertation work to their own inputs and circumstances. As pumping energy and leak management will be a major component of any WDS's footprint, the tool and efficiency analysis presented in this dissertation should act as a guide to evaluating GHG reduction efforts. For any WDS concerned with leaks and pipe replacement scheduling, the breakeven analysis tool is a starting point to understanding pumping energy, leaks, and GHG emissions.

As discussed in the policy implications, a marginal reduction in leaks at the national level could substantially reduce U.S. GHG emissions. Based on the scenario analyses, this could be cost effective. If the federal government decides to target WDSs and distribution leaks as a means of GHG reduction through policy or programs, focusing on WDSs that currently experience high losses from leaks and finding the most effective strategies in reducing those leaks is the first step. These utilities represent the most cost-effective opportunities for reducing GHGs through leak reduction. This effect will require an infusion of funding either at the state of federal level for utilities operating on a tight budget.

After successfully identifying strategies for reducing leaks in these utilities, similar utilities can be targeted and the same strategies can be implemented. Empowering the local managers to institute these changes will ensure that the drive for continual improvement in leak reduction will become a part of the utility's culture. Asset management can be a powerful tool in aiding this effort as utilities who adopt AM as part of their culture at every level will inherently seek to reduce waste and losses whenever possible.

9. Research Contributions

9.1 Summary of Contributions

This research sought to create the most up-to-date assessment methods for previously neglected components of U.S. WDSs, and to use the results to create meaningful and effective solutions for drinking water utilities. The existing related literature has several gaps. The WDS literature employing LCA has used data of poor quality for certain WDS aspects, such as water storage, or excluded aspects altogether, such as water wells. Other environmental assessments of WDSs has focused on theoretical problems that, while providing interesting approaches to design problems, has not created solutions that typical utilities could act upon and apply in practice. By identifying these gaps in the current body of research, these questions were introduced:

- What are the biggest contributors to GHG emissions of common U.S. WDS elements and how can these emissions be cost-effectively reduced?

- How do leaks in distribution impact the overall GHG footprint of a WDS? How can these impacts be reduced and what are the associated economic costs?

- How can we better understand how decisions are made by drinking water utilities to effectively communicate cost-effective opportunities for reducing GHG emissions?

Each of these questions was answered in this dissertation.

The LCA portion of the research focused on using the highest quality data to detail new contributions to WDS environmental assessment and improve on previous studies. The case study utility's cooperation in providing their material inventory, electricity purchases, design details, and supply chain characteristics allowed for a significant contribution to this particular goal. New LCA data were identified and applied to the case study utility's specifics, including steel materials, and plastics pipes. The as-built details for water storage, booster pumps, and water wells allowed for a new level of detail to be achieved in WDS analyses. This research applied LCA electricity emission factors whenever possible, which had not previously been done in the literature.

These new WDS LCA contributions created LCI results where the largest contributors to total GHGs could be clearly identified. The results were given context by applying projections for demand growth and decarbonization of the electricity mix.

Based on the LCI results for the case study utility, where pumping energy contributed 84% of the total GHG emissions, a relationship for the embedded emissions in delivered water was established. The case study utility's concern for better understanding of the environmental impacts of pipe replacement was combined with the research objective of quantifying the impacts of leaks in distribution. The breakeven tool was designed to contrast leaks and head losses with pipe replacement GHG emissions with the goal of providing utilities with a means of evaluating replacement schedules from an environmental perspective.

More context was given to the breakeven tool result by applying the case study utility's estimates for economic costs of pipe replacement. Multiple options for reducing leaks in distribution were detailed for avoided GHG emissions and pipe replacement economic costs, resulting in a method for other utilities to evaluate the options in reducing leaks from multiple perspectives. The carbon abatement costs of the different leak reduction options were calculated and proved to be a cost-effective option when compared to incorporating photovoltaics into the electricity mix. By this metric, reducing leaks can now be thought of an important option when seeking to cost-effectively reduce GHGs for policy makers.

This dissertation connected tools and results with the potential policy implications looming for WDSs. GHG emission limits for specific industries will be prevalent across the United States in the near future, and as a major consumer of electricity, WDSs will surely be targeted for emission reductions. The scenario analyses performed for California and Texas showed that GHG intensities of drinking water will vary for different regions, and that CACs of reducing leaks has diminishing returns when targeting utilities with lower distribution losses.

For utilities where reducing leaks significantly may be cost prohibitive, GHG savings can be achieved through other means: by water conservation or reducing the pumping head demand. Pumping head could be significantly reduced if fire flow requirements could be avoided as the pressure demands from these requirements greatly increase total pumping head. Water conservation is potentially the simplest way to reduce GHG emissions from an engineering standpoint, but has significant societal, such as lifestyle changes, and economic impacts, such as shifting from water intensive industries, that will make conservation goals difficult to achieve.

Although the case study utility has several atypical aspects, the tools and methodologies presented in this dissertation can be applied readily to U.S. WDSs with similar infrastructure features. This is especially true for aspects such as water storage, pipelines, water wells, booster pumps, and construction. Creating a detailed LCI will allow a utility to determine the best options for GHG emission reductions, and applying CAC analysis will determine cost-effective solutions. For most U.S. WDSs, these solutions will be based on reducing the embedded emissions in drinking water, and protecting this water as it is being distributed.

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Appendix A: Electricity Mixes and Emission Factors

Much of the LCA model developed in this dissertation is sensitive to geographical considerations, as discussed in Chapter 8. This is especially true of electricity mixes which vary considerably between countries, regions and states. The electricity mix used in carrying out a process or producing a product shaped several facets of this research: plastic pipes, asphalt production, and pumping energy. As detailed in Chapter 5, the decarbonization of the case study utility's mix would result in a substantial reduction in GHGs even without any new leak maintenance efforts. Electricity mixes were also crucial in Section 8.1, where Texas, although maintaining a much lower loss percentage, had a higher GHG intensity of drinking water than the case study utility due to a fossil-fuel intensive mix.

The electricity mixes used in the life-cycle inventory must remain confidential to protect the identity of the case study utility and its supply chain. The two electricity mixes used in Section 8.1 are detailed in Table 32.

	Coal	**Natural Gas**	**Oil**	**Other Fossil**	**Biomass**	**Hydro**
Texas	36%	49%	0.3%	0.9%	0.3%	0.4%
California	1.1%	55%	1.1%	1.0%	2.7%	13%

	Nuclear	**Wind**	**Solar**	**Geo-thermal**	**Other**	**g $CO_{2(eq)}$ /kWh**
Texas	10%	2.2%	0.0%	0.0%	0.2%	860.5
California	17%	2.6%	0.3%	6.2%	0.1%	557.1

Table 32. Electricity mix details and GHG intensity for Section 8.1 scenario analyses. Source: (1).

The emission factors used to determine the GHG intensities in Table A1 are taken from a report where emission factors were detailed based on existing LCA data.[2] These emission factors are displayed in Table 33.

Technology	$CO_{2(eq)}$ (g/kWh) Min	Max
Coal	607	1506
Oil	459	900
Natural Gas	311	1590
Nuclear		
Light Water	2.8	130
Heavy Water	0.2	120
Hydropower		
Reservoir	5	50
Run of River	0	44
Biomass		
Forestry Wood	27	86
Wastewood	15	101
Solar		
Solar Park	21	279
Distributed Solar	39	217
Residential Solar[3]	123.6	N/A
Solar Thermal	14	N/A
Wind		
Onshore	9.7	N/A

Table 33. Electricity generation emission factors based on LCA data. Source: (2), residential solar source: (3).

Averages were taken for all the emission factors listed in Table A2 to create a single emission factory for each generation technology. The residential solar emission factor was taken from a separate study.[3]

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Appendix B: GHG Intensities of Water Supply in California and Texas

This appendix details the applied GHG intensities that were used as part of the analysis in Section 8.1. Treatment values were taken from *(1)*. Transmission and distribution energy intensities were taken from *(2)* and applied to the associated electricity mixes detailed in Appendix A. California total water consumption was available by water supply source,[3] where Texas only had data available by end use sector.[4]

Surface Water	**MG/yr**	**% of Total**	**Treatment g $CO_{2(eq)}$/gal**	**High Trans-mission g $CO_{2(eq)}$/gal**	**Low Trans-mission g $CO_{2(eq)}$/gal**	**Best Estimate Trans-mission g $CO_{2(eq)}$/gal**
Local Deliveries	11,828,016	44%	0.41	3.90	0.00	0.00
Local Imported Deliveries	286,391	1%	0.41	3.90	0.00	0.00
Colorado River Deliveries	1,366,197	5%	0.41	7.80	3.90	7.80
CVP Base and Project Deliveries	2,790,103	10%	0.41	7.80	3.90	7.80
Other Federal Deliveries	186,224	1%	0.41	7.80	3.90	7.80
SWP Deliveries	1,111,414	4%	0.41	7.80	3.90	7.80
Groundwater Net Withdrawal	1,592,110	6%	0.41	3.90	0.00	0.00
Deep Percolation of Surface and GW	2,329,121	9%	0.41	3.90	0.00	0.00
Return Flow from Carryover Storage	43,208	0%	0.41	3.90	0.00	0.00
Recycled						
Reuse Surface Water	5,326,205	20%	0.00	0.00	0.00	0.00
Recycled Water	77,422	0%	0.39	0.00	0.00	0.00
Desalination	1,271	0%	7.36	0.00	0.00	0.00
TOTAL	26,937,681	100%		50.69	15.60	31.20

Table 34. Treatment and transmission GHG intensities for California organized by water supply source.

Surface Water	High Distri-bution g $CO_{2(eq)}$/gal	Low Distri-bution g $CO_{2(eq)}$/gal	Best Estimate Distri-bution g $CO_{2(eq)}$/gal	High Weighted GHG Intensity	Low Weighted GHG Intensity	Best Estimate Weighted GHG Intensity
Local Deliveries	0.74	0.43	0.58	2.22	0.37	0.44
Local Imported Deliveries	0.74	0.43	0.58	0.05	0.01	0.01
Colorado River Deliveries	0.74	0.43	0.58	0.45	0.24	0.45
CVP Base and Project Deliveries	0.74	0.43	0.58	0.93	0.49	0.91
Other Federal Deliveries	0.74	0.43	0.58	0.06	0.03	0.06
SWP Deliveries	0.74	0.43	0.58	0.37	0.20	0.36
Groundwater Net Withdrawal	0.74	0.43	0.58	0.30	0.05	0.06
Deep Percolation of Surface and GW	0.74	0.43	0.58	0.44	0.07	0.09
Return Flow from Carryover Storage	0.74	0.43	0.58	0.01	0.00	0.00
Recycled						
Reuse Surface Water	0.00	0.00	0.00	0.00	0.00	0.00
Recycled Water	1.84	0.74	1.29	0.01	0.00	0.00
Desalination	0.74	0.43	0.58	0.00	0.00	0.00
TOTAL	9.19	5.02	7.11	4.83	1.47	2.38

Table 35. Distribution and total weighted GHG intensities (based on the percentage allocated from each water source) for California. Weighted intensities are a sum of treatment, transmission and distribution.

End Use	MG/yr	% of Total	Treatment g $CO_{2(eq)}$/gal	High Trans-mission g $CO_{2(eq)}$/gal	Low Trans-mission g $CO_{2(eq)}$/gal	Best Estimate Trans-mission g $CO_{2(eq)}$/gal
Municipal Ground Water	502,074	11%	0.426	0.00	0.00	0.00
Municipal Surface Water	851,884	19%	0.426	0.00	0.00	0.00
Manufacturing Ground Water	69,224	2%	0.426	6.02	0.00	0.00
Manufacturing Surface Water	285,374	6%	0.426	6.02	0.00	0.00
Mining Ground Water	48,808	1%	0.426	6.02	0.00	6.02
Mining Surface Water	30,683	1%	0.426	6.02	0.00	6.02
Power Ground Water	14,455	0%	0.426	6.02	0.00	0.00
Power Surface Water	131,749	3%	0.426	6.02	0.00	0.00
Irrigation Ground Water	1,859,808	41%	0.426	6.02	0.00	0.00
Irrigation Surface Water	633,074	14%	0.426	6.02	0.00	0.00
Livestock Ground Water	48,562	1%	0.426	6.02	0.00	0.00
Livestock Surface Water	49,442	1%	0.426	6.02	0.00	0.00
TOTAL	4,525,137	1	5.11	60.24	0.00	12.05

Table 36. Treatment and transmission GHG intensities for Texas organized by water end use. All supply sources are assumed to be freshwater.

End Use	High Distri-bution g $CO_{2(eq)}$/gal	Low Distri-bution g $CO_{2(eq)}$/gal	Best Estimate Distri-bution g $CO_{2(eq)}$/gal	High Weighted GHG Intensity	Low Weighted GHG Intensity	Best Estimate Weighted GHG Intensity
Municipal Ground Water	1.17	0.68	0.92	0.13	0.08	0.10
Municipal Surface Water	1.17	0.68	0.92	0.22	0.13	0.17
Manufacturing Ground Water	1.17	0.68	0.92	0.11	0.01	0.01
Manufacturing Surface Water	1.17	0.68	0.92	0.45	0.04	0.06
Mining Ground Water	1.17	0.68	0.92	0.08	0.01	0.07
Mining Surface Water	1.17	0.68	0.92	0.05	0.00	0.05
Power Ground Water	1.17	0.68	0.92	0.02	0.00	0.00
Power Surface Water	1.17	0.68	0.92	0.21	0.02	0.03
Irrigation Ground Water	1.17	0.68	0.92	2.96	0.28	0.38
Irrigation Surface Water	1.17	0.68	0.92	0.08	0.01	0.00
Livestock Ground Water	1.17	0.68	0.92	0.08	0.01	0.01
Livestock Surface Water	1.17	0.68	0.92	0.08	0.01	0.01
TOTAL	14.00	8.17	11.09	4.46	0.59	0.90

Table 37. Distribution and total weighted GHG intensities (based on the percentage allocated from each water source) for California. Weighted intensities are a sum of treatment, transmission and distribution.

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