WATER DISTRIBUTION SYSTEM DESIGN AND REHABILITATION UNDER CLIMATE CHANGE MITIGATION SCENARIOS

by

Ehsan Roshani

A thesis submitted to the Department of Civil Engineering

In conformity with the requirements for

the degree of Doctor of Philosophy

Queen’s University

Kingston, Ontario, Canada

(April 2013)

Copyright © Ehsan Roshani, 2013
To My Father
Abstract

The water industry is a heavy consumer of electricity to pump water. Electricity generated with fossil fuel sources produce greenhouse gas (GHG) emissions that contribute to climate change. Carbon taxation and economic discounting in project planning are promising policies to reduce GHG emissions. The aim of this research is to develop novel single- and multi-objective optimization frameworks that incorporate a new gene-coding scheme and pipe ageing models (pipe roughness growth model, a pipe leakage model, and a pipe break model) to examine the impacts of a carbon tax and low discount rates on energy use, GHG emissions, and design/operation/rehabilitation decisions in water systems. Chapter 3 presents a new algorithm that optimizes the operation of pumps and reservoirs in water transmission systems. The algorithm was applied to the KamalSaleh transmission system near Arak, Iran. The results suggest that a carbon tax combined with a low discount rate produces small reductions in energy use and GHG emissions linked to pumping given the high static head of the KamalSaleh system. Chapter 4 presents a new algorithm that optimizes the design and expansion of water distribution networks. The algorithm was applied to the real-world Fairfield water network in Amherstview, Ontario, Canada. The results suggest that a carbon tax combined with a low discount rate does not significantly decrease energy use and GHG emissions because the Fairfield system had adequate installed hydraulic capacity. Chapters 5 and 6 present a new algorithm that optimizes the optimal rehabilitation type and timing of water mains in water distribution networks. In Chapter 5, the algorithm is applied to the Fairfield network to examine the impact of asset management strategies (quantity and infrastructure adjacency discounts) on system costs. The results suggest that applying discounts decreased capital and operational costs and favored pipe lining over pipe replacement and duplication. In Chapter 6, the water main rehabilitation optimization algorithm is applied to the Fairfield network to examine the impact of a carbon tax and low discount rates on
energy use and GHG emissions. The results suggest that adopting a low discount rate and levying a carbon tax had a small impact in reducing energy use and GHG emissions and a significant impact in reducing leakage and pipe breaks in the Fairfield system. Further, a low discount rate and a carbon tax encouraged early investment in water main rehabilitation to reduce continuing leakage, pipe repair, energy, and GHG costs.
Co-Authorship

This thesis represents mainly original work by the author; however, significant contributions were made by co-authors who collaborated in interpreting the results and preparing journal and conference papers, some of which have been used in modified forms as chapters in this thesis. Chapters 3, 4, 5, and 6 were written as independent journal manuscripts that have been published in, or submitted to, peer-reviewed journals. Dr. Yves Filion, provided intellectual supervision and editorial comments for all chapters and is a co-author of all the manuscripts. Stephanie P. MacLeod, M.A.Sc., is also a co-author of Chapter 4. Stephanie prepared the case study data and helped in the preparation and writing of the manuscript.
Acknowledgements

I would like to express my sincere gratitude to my supervisor, Dr. Yves Filion, for his encouragement, patience and guidance throughout the course of the project and also for his incredible generosity with his time and knowledge. His constructive suggestions and comments on my work have been invaluable, and have enabled me to develop this research to its fullest potential. I enjoyed the privilege of doing this research with him. I have benefited immensely from his support and I consider myself lucky to have worked with Dr. Filion. I am deeply indebted for all his efforts.

I also would like to gratefully acknowledge Stephanie P. MacLeod, M.A.Sc., who played an essential role in the success of this thesis. Stephanie contributed immensely in preparing Chapter 4. My warmest regards goes to David Thompson, P.Eng. and Jason Sands at Loyalist Township for providing invaluable information and professional contribution to the development of this thesis. This research was financially supported by Queen’s University and the Natural Sciences and Engineering Research Council (NSERC).

I am sincerely thankful to Dr. Ian Moore at Queen’s University, Dr. Ahmad Malekpour and Dr. Bryan Karney at University of Toronto, Dr. Steven Buckberger at University of Cincinnati, Dr. Zoran Kapelan at University of Exeter, and Dr. Kevin Lansey at University of Arizona for valuable discussion and encouragement and for sharing their practical experiences with me.

I would like to thank Ms. Maxine Wilson and Mr. Bill Boulton at the Department of Civil Engineering at Queen’s University for their incredible support. In addition I would like to thank my friends, A. Kanani, L. Herstein, Dr. R. Valipour, A. Oldford, and H. Swartz for their input, support, and friendship.
I would also like to acknowledge the contribution made by my parents Omran and Fozieh Roshani and my sisters Kosar and Elham. Thank you for your support and endless encouragements. Finally, I must express my deepest gratitude to my love, Rezvan, whose unconditional love and support through the last 10 years gave me the strength and hope to live.
# Table of Contents

Abstract .....................................................................................................................................iii  
Co-Authorship ...........................................................................................................................v  
Acknowledgements ...................................................................................................................vi  
List of Figures ..........................................................................................................................xiii  
List of Tables ............................................................................................................................xv  

Chapter 1 Introduction .................................................................................................................1  
1.1 Research Background ........................................................................................................1  
1.2 Research Objectives ..........................................................................................................7  
1.3 Thesis Organization ...........................................................................................................9  
1.4 Publication Related to the Thesis .....................................................................................10  
1.4.1 Journal Papers ...........................................................................................................10  
1.4.2 Papers in Conference Proceedings .............................................................................11  
1.5 References .......................................................................................................................12  

Chapter 2 Problem Definition and Literature Review .....................................................................19  
2.1 Water distribution system design, expansion and rehabilitation as an optimization problem. .................................................................19  
2.1.1 WDS Design .............................................................................................................21  
2.1.2 WDS Expansion .......................................................................................................21  
2.1.3 WDS Operation ........................................................................................................26  
2.1.4 WDS Rehabilitation .................................................................................................29  
2.2 Incorporating economic measures to mitigate GHG emission in the problem formulation.34  
2.3 GA-Based Single- and Multi-Objective Optimization ..........................................................38  
2.3.1 Introduction to the GA .............................................................................................38  
2.3.2 GA operators ............................................................................................................40  
2.3.3 Single-Objective GA, Elitist GA ................................................................................42  
2.3.4 Multi-Objective GA, NSGA-II ..................................................................................42  
2.3.5 Penalty Functions ......................................................................................................44  
2.4 OptiNET ..........................................................................................................................44  
2.4.1 Asset Management and Model Validation ...................................................................45  
2.5 Research Contributions ....................................................................................................46
2.5.1 Publication 1: “Impact of Uncertain Discount Rates and Carbon Pricing on the Optimal Design and Operation of the KamalSaleh Water Transmission System” .................................48
2.5.2 Publication 2: “Evaluating the Impact of Climate Change Mitigation Strategies on the Optimal Design and Expansion of the Fairfield, Ontario Water Network: A Canadian Case Study” .................................................................................................................................49
2.5.3 Publication 3: “Event-Based Approach to Optimize the Timing of Water Main Rehabilitation While Considering Asset Management Strategies” ..........................................................50
2.5.4 Publication 4: “Water Distribution System Rehabilitation under Climate Change Mitigation Scenarios in Canada” ........................................................................................................51

2.6 References ..................................................................................................................................................................................52

Chapter 3 Impact of Carbon-Mitigating Strategies on Energy Use and Greenhouse Gas Emissions in the KamalSaleh Water Transmission System: A Real Case Study ........................................65

3.1 Abstract ..........................................................................................................................................................................................65

3.2 Introduction ....................................................................................................................................................................................66
  3.2.1 Economic Instruments to Mitigate GHG Emissions ..................................................................................................................66
  3.2.2 Previous Research in the Optimization of Sustainable Water Distribution Networks .........................................................................68

3.3 KamalSaleh Water Transmission: Single-objective and Multi-objective Optimization ........................................................................72
  3.3.1 Multi-Objective Optimization Formulation ..................................................................................................................................74
  3.3.2 Single-Objective Optimization Formulation ..................................................................................................................................77
  3.3.3 Optimization Constraints .................................................................................................................................................78
  3.3.4 Reservoir and Pump Operation Constraints ..............................................................................................................................79

3.4 Gene Coding Scheme for Pump Scheduling .................................................................................................................................81
  3.4.1 Elitist Genetic Algorithm .......................................................................................................................................................82
  3.4.2 Non-Dominated Sorting Genetic Algorithm (NSGA-II) ................................................................................................................82

3.5 Case Study: KamalSaleh Water Transmission Pipeline ..................................................................................................................83

3.6 Single-Objective Optimization Results .................................................................................................................................................86
  3.6.1 Impact of Discount Rate on Optimal Design, Costs, Electricity Use, and GHG Emissions ......................................................................................87
  3.6.2 Impact of a Carbon Tax on Optimal Design, Costs, Electricity Use, and GHG Emissions ...................................................................................88
  3.6.3 Combined Impact of a Carbon Tax and Discount Rates on the Optimal Design, Costs, Electricity Use, and GHG Emissions ........................................88

3.7 Multi-Objective Optimization Results .................................................................................................................................................89
Chapter 4 Evaluating the Impact of Climate Change Mitigation Strategies on the Optimal Design and Expansion of the Fairfield, Ontario Water Network: A Canadian Case Study

4.1 Abstract
4.2 Introduction
4.3 Research in Planning, Design, and Optimization of Water Distribution Networks for Environmental Sustainability
  4.3.1 NRTEE Carbon Pricing
  4.3.2 Social Discount Rates Suggested by the Treasury Board of Canada
4.4 Problem Formulation
4.5 Case Study: Optimization of the Fairfield Water Distribution Network
  4.5.1 Demand Conditions
  4.5.2 Capital Costs
  4.5.3 Operational Cost
  4.5.4 GHG Emissions
  4.5.5 GHG Cost
4.6 Results
4.7 Discussion
4.8 Summary and Conclusions
4.9 Acknowledgments
4.10 References

Chapter 5 Event-Based Approach to Optimize the Timing of Water Main Rehabilitation with Asset Management Strategies

5.1 Abstract
5.2 Introduction
5.3 Problem Definition
5.4 Event-Based Rehabilitation: A New Approach to Gene Coding
5.5 Asset Management Strategies
5.6 Model Implementation
5.7 Fairfield Water Distribution Network
5.7.1 Pipe Leakage Model ........................................................................................................146
5.7.2 Break Model ..................................................................................................................147
5.7.3 Pipe Roughness Growth Model .....................................................................................148
5.8 Asset Management Scenarios and Results ........................................................................149
  5.8.1 Pareto-Fronts of Scenarios 1 Through 4 ......................................................................149
  5.8.2 Impact of the Budget Constraint and Discounts on Capital and Operational Costs ... 152
  5.8.3 Impact of Discounts on the Geographic Location of Rehabilitated Pipe ..................153
  5.8.4 Impact of Budget Constraint and Discounts on the Occurrence of Rehabilitation Events ........................................................................................................................................155
  5.8.5 Impact of Budget Constraint on the Annual Costs ....................................................157
5.9 Sensitivity Analysis .........................................................................................................159
5.10 Summary and Conclusions ............................................................................................161
5.11 Acknowledgements .......................................................................................................162
5.12 References ....................................................................................................................162

Chapter 6 Water Distribution System Rehabilitation under Climate Change Mitigation Scenarios in Canada ................................................................................................................................167
6.1 Abstract ............................................................................................................................167
6.2 Introduction ......................................................................................................................167
  6.2.1 Greenhouse Gas Emissions, Carbon Tax, and Economic Discounting in Canada .... 168
6.3 Review of Previous Research in Network Rehabilitation and Sustainable Network Design ........................................................................................................................................170
6.4 Problem Definition .........................................................................................................173
  6.4.1 Leak Forecasting Model ............................................................................................174
  6.4.2 Break Forecasting Model ..........................................................................................175
  6.4.3 Pipe Roughness Growth Forecasting Model ...............................................................176
  6.4.4 Model Implementation .............................................................................................176
6.5 Fairfield Water Distribution Network ...............................................................................178
6.6 Results and Discussions ................................................................................................181
  6.6.1 Effect of Discount Rate and Carbon Tax on the Location of Pareto Fronts .............182
  6.6.2 Effect of Discount Rate and Carbon Tax on Energy Use and GHGs ......................184
  6.6.3 Effect of Discount Rate and Carbon Tax on Water Loss and Break Repair Cost ......189
  6.6.4 Effect of Discount Rate and Carbon Tax on Rehabilitation Decision Type and Timing ........................................................................................................................................189
6.6.5 Differences in Leakage Costs, Pipe Break Repair Costs, and Energy Costs across Minimum Capital Cost Solutions and Minimum Operational Cost Solutions .......... 191
6.7 Sensitivity Analysis ........................................................................................................ 193
  6.7.1 Capital Costs ....................................................................................................... 194
  6.7.2 Operational Costs .............................................................................................. 195
  6.7.3 Greenhouse Gas Emissions .............................................................................. 197
6.8 Summary and Conclusions ....................................................................................... 197
6.9 Acknowledgements ................................................................................................... 197
6.10 References .............................................................................................................. 198

Chapter 7 Conclusions ................................................................................................. 204
  7.1 Overall Research Contributions ............................................................................. 204
    7.1.1 Model Development ...................................................................................... 205
    7.1.2 Scenario Analyses ......................................................................................... 206
    7.1.3 Research Findings in Case Studies ................................................................. 206
  7.2 Research Limitations ............................................................................................. 208
  7.3 Recommendation for Future Work ......................................................................... 209
  7.4 References ............................................................................................................. 210

Appendix A OptiNET Validation Results ..................................................................... 212
  Summery of test functions ......................................................................................... 212
  OptiNET test results vs. NSGA-II ............................................................................ 213
Appendix B Parallel Processing ..................................................................................... 218
  Abstract .................................................................................................................... 218
  Introduction ............................................................................................................... 218
  Methodology/Process ................................................................................................. 219
    Parallel Processing ................................................................................................. 219
    Message Passing Interface (MPI) ........................................................................... 220
    Task Parallel Library, TPL .................................................................................... 224
  Parallelism in Practice .............................................................................................. 225
  Results/Outcomes ..................................................................................................... 228
  Summery .................................................................................................................... 231
  References ................................................................................................................. 231

Appendix C The Optimization Specifications ............................................................... 233
List of Figures

Figure 2.1 The typical genetic algorithm flowchart ................................................................. 39
Figure 2.2 The schematic crossing diagram ............................................................................. 41
Figure 2.3 GA mutation schematic diagram ............................................................................ 42
Figure 2.4 The OptiNET graphical user interface ..................................................................... 45
Figure 2.5 Contribution of the four journal papers presented in this thesis in relation to the thesis objectives .................................................................................................................. 47
Figure 3.1 Schematic of KamalSaleh water transmission system .............................................. 73
Figure 3.2 Diurnal patterns used for first and second 25-year periods in the KamalSaleh water transmission pipeline .................................................................................................................. 75
Figure 3.3 Pump control logic used to operate the KamalSaleh water transmission system ...... 81
Figure 3.4 Non-dominated solutions generated for discounting and carbon tax: a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, where electricity discount rate = DR(elec), greenhouse gas cost discount rate = DR(GHG), carbon tax = CT .............................................................................................................. 91
Figure 4.1 Layout of Fairfield water distribution network ......................................................... 109
Figure 4.2 Fairfield water distribution system average-day diurnal curve (data from CH2M Hill 2007) .............................................................................................................................. 113
Figure 4.3 Forecasted Canadian greenhouse gas emission intensity factors (data from S & T Consultants Inc. 2008) .................................................................................................................. 117
Figure 4.4 Percent contribution of capital cost, operating cost and GHG cost to total cost for (a) PVC and (b) DCLI pipe materials .............................................................................................................. 118
Figure 5.1 Encoded genes in a chromosome for a single pipe and its duplicate ......................... 138
Figure 5.2 Effect of pipe length on quantity discount .................................................................. 141
Figure 5.3 Flow chart of OptiNET optimization model ............................................................... 142
Figure 5.4 Fairfield water distribution system ........................................................................... 144
Figure 5.5 Pareto fronts generated in asset management Scenarios 1 through 4 ....................... 150
Figure 5.6 Location of pipes that benefit from: a) adjacency and quantity discounts in Scenario 1 (Scn. 1-3), and b) adjacency and quantity discounts in Scenario 4 (Scn. 4-3) .................. 154
Figure 5.7 Time variation of annual total cost (capital cost + operational cost) for the minimum total cost solutions in Scenarios 1 through 4 ................................................................. 157
Figure 5.8 Time variation of annual leak volume for minimum total cost solutions in Scenarios 1 through 4.................................................................................................................................158
Figure 6.1 Flow chart of OptiNET water main rehabilitation timing optimization model........177
Figure 6.2 Schematic of Fairfield water distribution system.....................................................178
Figure 6.3 Pareto fronts generated in Scenarios 1 through 6......................................................183
Figure 6.4 Time variation of annual cost of lost water for minimum capital cost solution ("-1") and minimum operational cost solution ("-2") of Scenario 6 (CT=FD, DR=1.4%). .......................192

Figure A- 1 Non-dominated Pareto front obtained on SCH benchmark ....................................213
Figure A- 2 Non-dominated Pareto front obtained on FON benchmark .....................................214
Figure A- 3 Non-dominated Pareto front obtained on ZDT1 benchmark .................................214
Figure A- 4 Non-dominated Pareto front obtained on ZDT2 benchmark .................................215
Figure A- 5 Non-dominated Pareto front obtained on ZDT3 benchmark .................................215
Figure A- 6 Non-dominated Pareto front obtained on Constr benchmark .................................216
Figure A- 7 Non-dominated Pareto front obtained on SRN benchmark .................................216
Figure A- 8 Non-dominated Pareto front obtained on TNK benchmark .................................217

Figure B-1 Fairfield water distribution system ...........................................................................226
Figure B- 2 Part of the Graphical User Interface, GUI, developed to prepare the optimization models and to control the cluster machine .................................................................228
Figure B-3 Required time to evaluate all solutions in one generation with a different number of cores ......................................................................................................................................229
Figure B-4 Running acceleration achieved with the parallelism ..............................................230
List of Tables

Table 3-1 Hazen-Williams ‘C’ factors of transmission pipes in the KamalSaleh system in the first and second 25-year periods. .......................................................................................................77
Table 3-2 GHG mass, GHG cost, electricity cost, reservoir construction cost, and total cost for a range of discounting and carbon tax scenarios in the single-objective optimization of the KamalSaleh system. ...................................................................................................................85
Table 3-3 GHG mass, GHG cost, electricity cost, reservoir construction cost, and total cost for a range of discounting and carbon tax scenarios in the multi-objective optimization of the KamalSaleh system. ...................................................................................................................92
Table 4-1 NRTEE carbon price trajectories: “No tax”, “Slow and shallow” and “Fast and Deep” ...............................................................................................................................................105
Table 4-2 Rated head, rated flow, speed, rated efficiency, and tank controls for high-lift and booster pumps in the Fairfield network.................................................................................................................................110
Table 4-3 Diameter, length, and age of existing water mains in the Fairfield system (excluding Odessa) (CH2M Hill 2007). .................................................................................................................................111
Table 4-4 Fairfield annual water demand growth rates and current and future water demands (CH2M Hill 2007)......................................................................................................................................................112
Table 4-5 Unit costs of new commercially-available PVC and DCLI pipe diameters and unit cost of cleaning and cement-mortar lining existing pipes (from Walski 1986). ............................................114
Table 4-6 Capital cost, operating cost, GHG cost, and total cost of the Fairfield expansion for PVC and DCLI pipe materials under a range of discounting and carbon pricing scenarios. ........ 119
Table 4-7 Energy use and mass of GHG emissions in the Fairfield expansion for PVC and DCLI pipe materials under a range of discounting and carbon pricing scenarios. ..............................120
Table 4-8 Percent of mains duplicated, percent of mains cleaned and lined, percent of mains with no intervention for PVC and DCLI pipe materials under a range of discounting and carbon pricing scenarios. .................................................................................................................................121
Table 5-1 Pipe material and age distribution in Fairfield system............................................................................144
Table 5-2 Unit costs of commercially-available PVC pipes and their cleaning and lining costs (adapted from Walski 1986). ........................................................................................................................................145
Table 5-3 Projected annual growth rates and current and projected water demands in the Town of Amherstview ................................................................. 146
Table 5-4 Break distribution by pipe material and exponential model values ......................... 148
Table 5-5 Average annual costs, present value capital costs, present value operational costs, and present value total cost for asset management Scenarios 1 through 4 ......................................... 151
Table 5-6 Main length rehabilitated, age of rehabilitation, and percent of mains that benefit from discounts in the asset management Scenarios 1-4 ............................................................... 156
Table 5-7 The results of sensitivity analysis .......................................................................... 160
Table 6-1 NRTEE carbon tax trajectories ............................................................................ 169
Table 6-2 Pipe break data (number and pipe age at time of break) and calibrated and assumed parameters for the time-exponential pipe break forecasting model for the four pipe materials in the Amherstview network ................................................................. 175
Table 6-3 Pipe material, length, and age in the Fairfield system .............................................. 179
Table 6-4 Unit costs of commercially-available PVC pipes and their cleaning and lining costs (from Walski 1986) ........................................................................................................ 179
Table 6-5 Projected annual demand growth rates and current and projected water demands in the Town of Amherstview (from CH2MHIll 2007) .................................................................................. 180
Table 6-6 Average annual costs, annual greenhouse gas emissions, present value capital costs, present value operational costs, and present value total costs for select solutions generated in Scenarios 1 through 6 ................................................................. 186
Table 6-7 Main length rehabilitated, age of rehabilitation, and percent of mains rehabilitated for select solutions in Scenarios 1 through 6 ........................................................................................................ 187
Table 6-8 The length and percent of mains rehabilitated over the planning period for select solutions in Scenarios 1 through 6 ........................................................................................................ 188
Table 6-9 Results of the sensitivity analysis .......................................................................... 196
Tabel A-1 Benchmarks without constraint used to validate OptiNET .................................... 212
Tabel A-2 Benchmarks with constraints used to validate OptiNET ........................................ 213
Table C-1 The optimization specifications in each chapter ................................................... 233
Chapter 1

Introduction

1.1 Research Background

Constructing, maintaining, and rehabilitating water infrastructure is a costly and important endeavor for cities around the world (UN Habitat 2012). A study by Deb et al. (2002) indicated that $325 billion is needed to rehabilitate drinking water systems in the USA to maintain current service levels. An equivalent Canadian study indicated that $11.5 billion should be spent over the next 15 years to upgrade municipal water distribution systems (CWWA 1997). Most of the need is in replacing and rehabilitating deteriorated water mains in water distribution systems. In North America, water distributions systems leak at an average rate of 20-30% (Brothers 2001) and at comparable rates in Europe (European Environment Agency 2010). Water loss through leaks and pipe roughness growth in deteriorated water mains increase energy use and energy costs of pumping in water distribution systems.

Climate change and its negative impacts is seen as a major concern in both developed and developing countries. Reducing greenhouse gas (GHG) emissions is recognized as a valuable tool to mitigate unacceptable physical and financial damages linked to the future changes in climate (Stern et al. 2006). The water sector is a heavy consumer of electricity for raw water pumping in transmission systems and for pumping treated drinking water in distribution networks. For example in the UK, roughly 3% of generated electricity is consumed by the water industry (Ainger et al. 2009). Another estimate indicates that the energy used to pump, and heat water is approximately 13% of all US electricity generation (Griffiths-Sattenspiel & Wilson 2009). More than 60% of electricity is generated through the combustion of fossil-fuels (e.g., coal, natural gas) (IEA 2012) which releases GHGs such as carbon dioxide into the atmosphere. Considerable
portion of these GHG emissions is generated by the water industry. One study estimated that water provision and water heating accounts for 6% of GHGs emitted in the UK (Clarke et al. 2009). Economic instruments can play an important role to reduce GHG emissions. Indeed, many industrialized and developing countries including the United Kingdom, Australia, Canada, and Iran have begun, or are planning, to use financial measures such as levying carbon taxes, introducing carbon cap-and-trade systems, and using economic discounting in project planning to encourage large economic sectors and industries, including the water sector, to reduce their GHG emissions and mitigate predicted future damages caused by climate change. Under a carbon tax structure, government levies a tax on sectors that emit GHGs. Under a cap-and-trade system, government sets a maximum annual level of GHG emissions (the cap) that a sector is permitted to release without economic penalty. Sectors that emit GHGs below the maximum level can receive a credit for their unused emissions. Sectors that emit GHGs above the maximum level must buy carbon credits to cover these surplus emissions, usually from other sectors whose annual emissions are below the cap. Both tax and cap-and-trade system directly increase the electricity cost which is one of the major expenses in the water distribution system maintenance. This work will focus on the impact of a carbon tax on energy use and GHGs generated from pumping water in water distribution networks. Economic discounting is another instrument being considered to encourage sectors to reduce their GHG emissions. The social discount rate (SDR) is the minimum real rate of return that public projects must earn if they are to be worthwhile undertakings (Boardman et al. 2008). The SDR can have a significant impact on the economic analysis of a project especially for long-term projects with climate change implications. High SDRs reduce the influence of future operational costs (e.g., electricity costs, maintenance, etc.) on the net present value of a project. Conversely, low SDRs give greater weighting to future costs
and thus have the potential to lower GHG emissions linked to electricity use for pumping water in water distribution systems.

Water network design/expansion, operation and water network rehabilitation have different meanings in the field of water distribution systems analysis. Water network design and expansion optimization is concerned with sizing and locating system components such as pipes, pumps, and tanks to provide pressure at or above a minimum required to meet peak and off-peak demands, to meet fire flow requirements, and to meet water quality requirements while minimizing the construction and operation cost of the system (Boulos et al. 2004). In the design/expansion problem, component selection and sizing occur only at the start of the planning period of the system. Follow-up maintenance and system upgrades are not considered in the design problem.

What distinguishes the rehabilitation problem from the design/expansion problem is the time-dependent nature of decision variables in network rehabilitation. In aging networks, pipe wall conditions tend to deteriorate with time (wall roughness increases and inner diameter decreases), while leakage and pipe failures tend to increase with time. The rehabilitation problem seeks to optimize the type and timing of pipe replacement, repair, and lining interventions that will minimize overall system costs. System costs include the capital cost of replacing, repairing, and lining pipes, and the operation cost of pumping water to satisfy demands and the water lost to leakage and to other non-revenue uses (e.g., fire hydrants, etc.). Pipe replacement, repair, and lining activities are subject to constraints on minimum pressure and demand requirements, annual budgetary limits, and water quality and reliability requirements (Engelhardt et al. 2000). Unlike in the design/expansion problem, rehabilitation considers recurring replacement, repair, and lining interventions throughout the entire planning period of a water distribution system.
A number of optimization algorithms have been developed to search the large decision space in the pipe design/expansion, operation and rehabilitation problems. A comprehensive review of optimization algorithms developed to solve the pipe design/expansion problem is found in Lansey and Mays (1989a) and Lansey (2006). Previous research that has focused on the development of pipe rehabilitation optimization models and incorporated environmental considerations in optimization is briefly reviewed here. A more comprehensive review of optimization algorithms that solve the design, expansion, operation, and rehabilitation problems is presented in Chapter 2.

The water distribution network rehabilitation problem was initially formulated by Alperovits and Shamir (1977), Bhave (1978), and Deb (1976). These researchers framed network rehabilitation as a single-objective optimization problem with the objective to minimize the total cost of construction and operation. This is often referred to as the least-cost optimization problem. The least-cost criterion was used by Walski (1985 and 1986), and Walski and Pelliccia (1982) to replace pipes with break rates greater than the critical break rate. This criterion specifies that a pipe should be rehabilitated if the cost to rehabilitate is lower than the pumping cost without rehabilitation. Day (1982) also used of least-cost criterion and was the first to propose that water network rehabilitation be based on realistic and up-to-date hydraulic information and not just on pipe age. Non-linear optimization algorithms that included hydraulic solvers for updating of pipe hydraulic conditions under a wider range of demands and pump failure scenarios were developed by Woodburn et al. (1987), Su et al. (1987), Lansey and Mays (1989), and Kim and Mays (1994). Kleiner et al. (1998a, 1998b) developed a rehabilitation framework based on dynamic programming and partial and implicit enumeration schemes to minimize the cost of rehabilitation over a pre-defined time horizon. Dandy and Engelhardt (2001) applied genetic algorithms to minimize the present value of capital, repair and pipe damage costs for a real pipe network in Adelaide, Australia.
More recently, researchers have applied multi-objective optimization algorithms to solve the network rehabilitation problem (Farmani et al. 2005; Ejeta and Mays 2002; and Lansey et al. 1989, 1992). In multi-objective approaches, the goal is to minimize one or more objectives that typically include cost and some form of system performance (e.g., network reliability). Dandy and Engelhardt (2006) proposed a multi-objective framework to minimize the rehabilitation costs and maximize network reliability simultaneously. A head-driven hydraulic model was first linked to a multi-objective genetic algorithm by Alvisi and Franchini (2006) to realistically simulate water leakage in rehabilitation planning. Jayaram and Srinivasan (2008) developed a multi-objective program to minimize the life-cycle cost of rehabilitation and maximize the hydraulic performance of a network.

Recently research has also focused on incorporating environmental considerations (e.g., energy use, release of emissions, etc.) in the network design and expansion problem. Filion et al. (2004) were the first to develop a decision support system to determine the timing of water main replacement based on life-cycle energy considerations in the fabrication, use, and disposal stages of a network. Dandy et al. (2006 and 2008) were the first to develop a multi-objective optimization algorithm that incorporates objectives of whole-of-life-cycle costs, energy use, GHG emissions, and resource consumption. Wu et al. (2008, 2010) used a multi-objective genetic algorithm (MOGA) to design a small, hypothetical water distribution network by minimizing its total present value cost and the mass of GHG emissions.

Previous studies have incorporated environmental objectives in the water distribution system design problem mainly to understand the effect of climate change mitigation scenarios on design decisions and on energy use and GHG emissions (Filion et al. 2004; Dandy et al. 2006 and 2008; Wu et al. 2008, 2010). Hypothetical, simplified networks have been used in most of these studies. The research results generated with these simple networks are not directly transferable to real,
complex networks and this is a current limitation of the previous research. To the authors’ knowledge, no approach to date has been proposed to investigate the impact of climate change mitigation strategies on the optimization of WDS expansion, operation, and the timing and type of water main rehabilitation. This is owing to the complexity of solving this problems which typically comprises a vast number of time-dependent variables such as rehabilitation and replacement decisions and pump status which requires a great deal of computational power to solve.

The major goal of this research is to identify the impact of a carbon tax and using low discount rates on the design/expansion, operation and rehabilitation of water distribution systems. There are several issues that must be addressed in order to carry out this research. First of all, the water distribution system design/expansion, operation and rehabilitation planning problems are formulated as single-objective and multi-objective approaches that include a carbon tax. Second, realistic climate change mitigation scenarios are defined by combining different carbon tax levels and discounting rates to examine their effect on energy use and the mass of GHGs generated in distribution networks. Third, appropriate single-objective and multi-objective optimization techniques are combined with a hydraulic model and pipe ageing models (e.g., pipe break forecasting model, leakage forecasting model, and wall roughness growth model) to simulate all aspects of the pipe deterioration including leakage, pipe breaks, and wall roughness growth. A novel gene-coding technique has been developed to increase the efficiency and speed of the search process. Fifth, the single-objective and multi-objective approaches are applied to complex, real-world water transmission and distribution systems.
1.2 Research Objectives

The main objective of this research is to develop an optimization framework that accounts for GHG emissions in the design/expansion, operation and rehabilitation of a water distribution network. The framework is used to examine the impact of climate change mitigation scenarios on design/expansion, operation and rehabilitation planning decisions as well as on the energy use and GHG emissions in optimal or near-optimal water distribution network solutions. The sub-objectives of the research are listed below.

Objective 1: Develop the single-objective and multi-objective frameworks to solve the network design/expansion, operation and rehabilitation problems;

Objective 2: Develop single-objective and multi-objective optimization framework with a novel gene-coding scheme and parallel computing techniques to reduce the complexity and computation requirements of the search process;

Objective 3: Combine the single-objective and multi-objective optimization algorithms with an appropriate hydraulic network solver, a pipe break forecasting model, a leakage forecasting mode, and a pipe wall roughness growth model.

Objective 4: Apply the single-objective and multi-objective algorithms to examine the impacts of a carbon tax and low discount rates on reservoir sizing and pump scheduling decisions in a complex, real-world water transmission pipeline system.

Objective 5: Apply the single-objective and multi-objective algorithms to examine the impacts of a carbon tax and low discount rates on design/expansion decisions, energy use, and GHG emissions in a complex, real-world water distribution system.

Objective 6: Apply the multi-objective algorithms to examine the impacts of asset management strategies on network rehabilitation decisions in a complex, real-world water distribution system;
**Objective 7:** Apply the multi-objective algorithms to examine the impacts of a carbon tax and low discount rates on network rehabilitation decisions, energy use, and GHG emissions in a complex, real-world water distribution system;

**Objective 8:** Perform a sensitivity analysis to examine the impact of uncertain parameters such as predicted demands, initial and growth rates in break growth model, initial and growth rates in leakage model, and Hazen-Williams coefficients on system costs, energy use, and GHG emissions in a complex, real-world water distribution system.

The first two objectives require investigating various optimization models and hydraulic simulators. In the literature various approaches have been used including mathematical programming, linear programming, non-linear programming, dynamic programming, and evolutionary algorithms (EA) (Shamir 1974; Savic and Walters 1997; Simpson et al. 1994; Gupta et al. 1999). Among these methods EA and specifically Genetic Algorithm proves to be effective for large water distribution systems (Simpson et al. 1994; Eusuff and Lansey 2003; Zecchin et al. 2007). Therefore single- and multi-objective GA are used in this research and it is combined with EpaNET2.0 (Rossman 2000) to perform the hydraulic simulations. Since the commercial optimization engines are not designed to handle problems with high number of decision variables, a new code must be developed for both single- and multi-objective GA engines. The combination of the first two objectives and objective 5 required enormous programming. Over 20,000 lines of code are written to prepare the model. The model benefits from extensive parallelization to reduce the computational time (for detail on parallel computing achievements please refer to the Appendix B). To achieve the third objective, a real water conveyance system (KamalSaleh, Markazi, Iran) with three pumping stations and 7 reservoirs is modeled to investigate the effect of considering GHG tax and social discount rate on pump scheduling and reservoir characteristics. In the fourth objective the impacts of various GHG mitigation scenarios are studied on the
expansion of a real water distribution system (Fairfield WDS, Ontario, Canada). In the fifth objective, three pipe deterioration models are developed to simulate the effect of pipe aging on the pipe characteristics in the WDSs including leakage growth, breakage growth, and wall roughness growth. To validate the outputs of the model as the sixth objective, Fairfield WDS rehabilitation planning is solved without considering the GHG mitigation scenario. Also the sensitive variables in the model are investigated in the seventh objective. And finally to fulfill the last objective, the effects of considering various GHG mitigation strategies are studied in the WDSs rehabilitation planning optimization problem, the model was applied on Fairfield WDS.

1.3 Thesis Organization

The doctoral thesis is comprised of seven chapters. Chapter 2 provides formal definitions for the water distribution system design/expansion, operation and rehabilitation optimization problems. Chapter 2 also includes a comprehensive review of previous research in the areas of water distribution system design/expansion, operation and rehabilitation optimization. The second chapter also explains how each of the four journal publications addresses the research objectives stated above. Chapter 3 presents the single-objective and multi-objective optimization models that account for GHG emissions and that are applied to the design of reservoirs and scheduling of pumps in the real-world KamalSaleh water transmission system in Iran. Chapter 4 presents the single-objective optimization models that account for GHG emissions in the network design/expansion problem. The models are applied to the real-world Fairfield water distribution in southeastern Ontario, Canada. Chapter 5 presents the multi-objective optimization models that account for asset management strategies in the network rehabilitation problem. In this chapter, the models are applied to the Fairfield water distribution network to examine the impacts of asset management strategies on system costs and the timing and type of rehabilitation decisions. In
Chapter 6, the multi-objective network rehabilitation optimization models are again applied to the Fairfield water distribution network to examine the impact of a carbon tax and low discount rates on energy use, GHG emissions and on the timing/type of rehabilitation decisions. In both Chapters 5 and 6, sensitivity analyses are performed to examine the impact of uncertain parameters (ex: predicted future demands, roughness coefficients, etc.) on the system costs, energy use, and GHG emissions. Chapter 7 summarizes the major research contribution of this thesis and discusses potential future directions for the research.

1.4 Publication Related to the Thesis

The research presented in this thesis resulted in the preparation of 4 journal papers published or submitted to peer-review journals (ASCE Journal of Water Resources Planning and Management and the Journal of Water and Climate Change) and 5 papers published in conference proceedings (Water Distribution System Analysis International Symposium and the Computing and Control in the Water Industry International Conference). The journal and conference papers (published and submitted) arising from the thesis are listed below:

1.4.1 Journal Papers


1.4.2 Papers in Conference Proceedings


1.5 References


Chapter 2
Problem Definition and Literature Review

2.1 Water distribution system design, expansion and rehabilitation as an optimization problem.

From the underground stone water canals in Persepolis and aqueducts in Athens to advanced water distributions systems in large modern cities, supplying clean water with an affordable cost has always been a concern of human societies. Water distribution systems are at the heart of this concern. The purpose of a WDS is to convey and distribute - at acceptable pressures - water that is of acceptable quality to meet user demands. Specifically, a minimum pressure must typically be met under average day, peak demand and fire flow conditions and a disinfectant residual must be maintained in the bulk water in the pipe and at the user’s faucet (Lansey et al. 1992). Network design, operation, and rehabilitation planning (in the case of existing systems) is required to meet these hydraulic and water quality performance standards.

Water distribution design/expansion is concerned with the optimal sizing and selection of components such as pipes, pumps, and tanks to meet pressure and water quality requirements and minimize construction and operation costs of the system (Boulos et al. 2004). In the design/expansion problem, component selection and sizing occur only at the start of the planning period of the system. Follow-up maintenance and system upgrades are not considered in the design problem. Water distribution operation is concerned with optimizing pumping schedules (time variation of on and off switches) to minimize the cost of pumping water in the system over a diurnal demand period that can span 24- to 72-hours. Water network rehabilitation seeks to optimize the type and timing of pipe replacement, repair, and re-lining interventions that will
minimize overall system costs. System costs include the capital cost of replacing, repairing, and re-lining pipes, and the operation cost of pumping water to satisfy demands and the water lost to leakage and to other non-revenue uses. Pipe replacement, repair, and re-lining activities are subject to constraints on minimum pressure and demand requirements, annual budgetary limits, and water quality and reliability requirements (Engelhardt et al. 2000). Unlike in the design/expansion problem, rehabilitation considers recurring replacement, repair, and re-lining interventions throughout the entire planning period of a water distribution system.

Whether one is undertaking network design/expansion, operation, or rehabilitation, the general optimization problem is formulated as searching for the “best” combination of decision variables that minimizes or maximizes an objective function while satisfying a number of constraints:

Given: a function $f(\bar{x}) : \bar{A} \rightarrow R^n$

Sought: an element $\bar{x}_o$ in $\bar{A}$ such that $f(\bar{x}_o) \leq f(\bar{x})$ for all $\bar{x}$ in $\bar{A}$ (minimization of objective function) or such that $f(\bar{x}_o) \geq f(\bar{x})$ for all $\bar{x}$ in $\bar{A}$ (maximization of objective function)

In which $f(\bar{x})$ is the objective function, $\bar{x}$ is the vector of decision variables. Typically, $\bar{A}$ is some sub-set of the Euclidean space, $R^n$ specifies the set of equality and inequality constraints that the members of $\bar{A}$ must satisfy. The domain $\bar{A}$ of $f$ is called the search space or the choice set, while the elements of $\bar{A}$ are called feasible solutions. The above framework will be used to define more specific optimization programs for the water distribution design/expansion, operation, and rehabilitation problems.
2.1.1 WDS Design

The aim of WDS design is to size and locate system components such as pipes, pumps, and tanks which minimize the overall cost of the system that includes up-front capital investments at the beginning of the project and continuing energy costs as in (1) over a specific planning horizon. This is subject to the constraints of continuity at nodes and energy conservation around pipe loops, minimum and maximum operating pressures, minimum and maximum fluid velocities, and minimum and maximum disinfectant residual concentrations.

\[
\text{Minimize}(TC) = (P_c + Pmp_c + Tank_c + ...) + Egy_c
\]  

(1)

In which \( TC \) is the total cost, \( P_c \) is the pipe cost, \( Pmp_c \) is the pump cost, \( Tank_c \) is the cost of elevated tanks, and \( Egy_c \) is the annual energy cost.

2.1.2 WDS Expansion

Contrary to the WDS design in which a distribution system is designed as one new system, the WDS expansion divides WDS into two subsystems. a) the current network, which has to be updated to satisfy future demands and b) the new WDS for future growth areas, which has to be designed and added to the current WDS. The decision variables for the current system often include pipe replacement, pipe lining and pipe duplication; while the decisions in the future expansion areas are the same as the WDS design problem (refer to section 2.1.1). The WDS expansion problem is subject to the same constraints as the WDS design problem. The WDS expansion is formulated as follows.

\[
\text{Minimize}(TC) = (R_c + L_c + D_c)_\text{current} + (P_c + Pmp_c + Tank_c + ...)_{\text{new}} + Egy_c
\]  

(2)

In which \( R_c, L_c, D_c \) are the pipe replacement cost, pipe lining cost, and pipe duplication cost for the current network and \( P_c, Pmp_c, Tank_c \) are the pipe cost, pump cost, and tank cost respectively,
for the future growth areas. Note that the tanks, pumps, and other components in the current network could also be renewed. These terms are eliminated for simplicity. The constructions (e.g. installing new pipes, building new tanks, etc.) for the new WDS and the network interventions (e.g. the pipe replacement, lining, and duplication) in the current WDS happen at the first year of planning. Therefore neither WDS design nor expansion deals with time-dependent decisions, which are the focus of the WDS operation and rehabilitation.

A large number of the early optimization approaches such as linear programming (Gupta et al. 1969; Jacoby 1968; Watanatada 1973; Kally 1971a; Morgan and Goulter 1985) continuous gradient formulation (Featherstone 1983), direct search techniques (Ormsbee and Contractor 1981), dynamic programming (Yang 1975; Kally 1971b), discrete gradients (Lam 1973) and integer programming (Rowell 1982; Oron and Karmeli 1979) have been reported to solve the WDS design/expansion in the literature before 1990. Although pipes are only available in discrete commercial diameters, most of these approaches considered the pipe diameter as a continuous variable. The main decision variable in these papers is often pipe diameter. Other WDS components such as the pumps, tanks, and valves have also been considered in the literature (Shamir 1974; Alperovits and Shamir 1979; Kher 1979; Deb and Sarkar 1971; Deb 1976; Calhoun 1971; Kareliotus 1984; Swamee 1973; Duan et al. 1990). Gessler (1985) proposed the selective enumeration method to reduce the number of solutions which need to be simulated and evaluated. In their method a heuristic algorithm was used to eliminate less appealing solutions before simulation. The proposed approach has two major problems. The computational requirement increases dramatically with the size of the network. Additionally, there is a possibility that a potential optimal solution is being eliminated in the process (Simpson et al. 1994).
The early mathematical optimization techniques have shown some limits especially when multi-objective optimization is required (Deb 2002; Coello Coello 2005). For instance some prior problem knowledge is required in all of these methods. Besides, the ability of finding the Pareto solutions (i.e. non-dominated solutions) is a function of the shape of the front in the mathematical techniques (Deb 2002). Another major problem in the most of these techniques is that constraints and objective functions should be differentiable. This makes it difficult to apply these techniques to WDS problems with a discrete search space. Developing stochastic optimization methods and advances in the computer science in the 1990s opened new opportunities in WDS analysis. The stochastic optimization models such as evolutionary algorithms, EAs, held promise to solve the discrete search space issue. They have been proven to overcome the multi-objective optimization challenges (Deb 2002).

Simpson et al. (1994) were the first to apply Genetic Algorithm, GA to the WDS design problem. The model was applied on a simple network that consists of 14 pipes and 2 reservoirs. The GA outcomes were compared with several other techniques such as complete enumeration and nonlinear programming. The results suggested that GA can find the global optimum with relatively few evaluations. Simpson and Goldberg (1994) investigated the factors that influence the performance of the simple GA in finding the optimal solution for a simple two-reservoir looped network. The results indicated that the use of a tournament selection scheme and the population size are the most critical aspects of applying the GA.

Dandy et al. (1996) modified the simple GA by applying fitness scaling, creeping mutation, and Gray coding. They solved the New York tunnel problem using the proposed modified GA. Although the new approach could find the least-cost solution, the major drawback of the approach was the tuning procedure for GA parameters (e.g. the population size, probability of the mutation and crossover). The modified GA outperformed the other traditional optimization
methods including the linear, nonlinear and dynamic programming. Savic and Walters (1997) were the first who combined GA with the EPANET hydraulic solver (Rossman 1994). They applied the proposed model on three benchmark networks (The two-reservoir looped network, Hanoi network, and New York City network). They successfully found the least-cost solutions for the design and expansion of these benchmarks. The outcomes showed the optimization results were sensitive to the Hazen-Williams coefficients used in the hydraulic modelling. Abebe et al. (1998) also linked EPANET with the global optimization tool (GLOBE). Four algorithms including the Controlled Random Search (CRS2) (Price 1983), CRS4 (Ali & Storey 1994), Genetic Algorithm (Goldberg 1989) and Adaptive Cluster Covering with Local Search (ACCOL) (Solomatine 1998) were used and compared. They concluded that GA and ACCOL outperform the other algorithms.

Halhal et al. (1997) solved the WDS design and expansion problem with the structured messy multi-objective GA optimization model. They maximized the benefit of WDS pipe replacement and lining subjected to a limited available budget and minimized the capital costs. The model was applied to two networks. The authors concluded that the structured messy GA performed better than the simple GA. Wu and Simpson (2001) applied the messy genetic algorithm to solve the WDS design and expansion problem. The proposed model was applied to a real water distribution system. They showed that the number of design trials required by the messy GA is considerably smaller than the other GAs. One of the important aspects of their work was to account for most of the network components including, the pipes, pumps, tanks, and valves.

Babayan et al. (2005) considered the demand uncertainty in solving the WDS design. They combined the Monte Carlo Simulation (MCS) with GA. Since MCS requires a large number of evaluations, the authors converted the original stochastic model to the deterministic formulation which uses the standard deviation as the measure of variability. Using this approach they were
able to quantify the impacts of uncertainty on the robustness of the system. The proposed model was then applied to the New York tunnel and Anytown benchmarks. The authors concluded that neglecting the uncertainty in the design process may lead to a serious under-estimation of the design variables.

More recently, Reca et al. (2008) evaluated the performance of several meta-heuristic optimization models including the GA, simulated annealing, Tabu search, and iterative local search. They first applied the models to the small Hanoi benchmark network. The models were then applied to a much larger irrigation network. They concluded that in the small Hanoi network, the GA outperformed the other algorithms, while in the larger network, the simulated annealing and Tabu searches performed better.

Because of the high costs of WDS construction, the main objective in the optimal design problem has been to minimize the capital costs of the project. Most of the early studies (abovementioned) only considered the construction costs in their objective function. Other objectives such as the operation and maintenance costs have also been incorporated in the WDS problems. Walski et al. (1987) considered the network maintenance cost and energy cost in the objective function. In another study, the operational costs of WDS were minimized as a separate objective (Boulos et al. 2001; Bounds et al. 2006). Since it is important to have a reliable and robust system in the long term, network reliability has also been considered as a separate objective or sometimes as a constraint in the WDS optimization frameworks (Mays et al. 1989; Schneiter et al. 1996; Wagner et al. 1988; Todini 2000; Ostfeld et al. 2002; Savic 2002; Keedwell and Khu 2004; Jourdan et al. 2005; Atiquzzaman et al. 2006; Kapelan et al. 2005; Jayaram and Srinivasan 2008). The WDS reliability is not the focus of this thesis therefore these works are not reviewed here.
2.1.3 WDS Operation

Contrary to the WDS design in which finding the optimal size for WDS components (e.g. the pipes, tanks, pump, etc.) is the main goal, the main focus of WDS operation is to find the optimal operational settings of pumps, tanks, and valves. The decision variables include the pump on and off status, valve open and close status and opening degree, and operational level of tanks. Several objectives have been considered in the literature to find the optimal WDS operation. These objectives include minimizing the energy costs, maximizing the system reliability, minimizing the system leakage, maximizing the harvested energy using micro turbines, and reducing the number of system components such as pressure-reducing valves. The most common WDS operation problem is the pump scheduling which deals with reducing the energy costs. In the general form, the WDS operation could be formulated as the following:

\[
\text{Minimize}(OC) = PC(E_p, t) \tag{3}
\]

In which \( OC \) is the operational cost and \( PC(E_p, t) \) is the pumping cost which is a function of the time \( t \) and energy price \( E_p \). This is often subject to several constraints including:

a) The conservation of mass and energy

b) The pump specification limits, such as number of on/off switches and the time between each on/off cycle.

c) Valve specification constraints

d) Tank operation constraints

Generally, an extended period simulation for 24 hours is required to simulate the diurnal demand pattern to find the optimal WDS operation, while in the WDS design and expansion only one single demand is simulated as a common approach to model the loads. Much of the early
researches on this topic were started during the 1980s and 1990s in which the linear programming was used to optimize the pump scheduling (Little and McCrodden 1989; Jowitt and Germanopoulos 1992). Other methods such as the nonlinear programming, dynamic programming, mixed and integer programming were used to minimize the energy costs as a single-objective optimization problem (Zessler and Shamir 1989; Lansey and Awumah 1994; Yu et al. 1994) A comprehensive review of these primary models was presented by Ormsbee and Lansey (1994).

Zessler and Shamir (1989) applied the progressive optimality and dynamic programming methods to solve the WDS operation problem. A 24-hour demand pattern was used to simulate the loads in the system. They included the initial and final water levels in the tanks as the design constraints. They also incorporated the variable energy cost within a 24 hour simulation. Lansey and Awumah (1994) used the dynamic programming to minimize the energy cost of the WDS operation. Various practical constraints including the limit to the number of pumps that are switched on, water level in the tanks, maximum energy consumption, and the rate of change in the tank water level were considered for the first time in the proposed model. A two-step approach was adopted. In the first step, the system hydraulic characteristics were analyzed. Then the optimization procedure was performed in the second step. The model was applied to a small size system. The authors concluded that the dynamic programming could be used to solve the pump scheduling problems in an on-line mode.

Sakarya and Mays (2000) were the first to consider water quality measures to find the optimal WDS operation. They combined the hydraulic and water quality model, EPANET, with the nonlinear optimization code to minimize three separate objectives. (1) The total energy cost (2) The deviations of actual substance concentrations from the desired concentration values, and (3) the total pump duration times. The model was applied to a hypothetical WDS. The authors
concluded that minimizing the total operational time or total cost, produces the optimal pump schedules that satisfy the water quality constraints. Results suggested that minimizing the concentration deviations reduces the pump operation time to a level that just satisfies the water quality considerations without considering the operational or economical factors.

McCormick and Powell (2003) proposed a new approach to find the optimal plan for the pump scheduling when an energy maximum demand charge is applied. The method incorporates the uncertainties for the future average and maximum day demands. This approach was based on building a cost function for the daily pump schedule decision making by repeating the energy cost optimization. The model was applied to a hypothetical and simple system. The authors claimed that the proposed approach has considerable advantages over the heuristic techniques due to the fact that it allows accounting for the demand uncertainties.

A more sophisticated method based on the artificial neural network, ANN, and GA was developed by Rao et al (2007) to find the real time, near optimal control setting for WDS. The ANN was used to predict the consequences of various control settings and GA was adopted to search the best settings. The approach accounted for the short time demand fluctuations, electricity tariff, and operational constraints. The proposed model was also applied to a hypothetical system. Broad et al (2009) developed a method to use the meta-modeling to find the optimal operation of hydraulically complex systems. The approach starts with the simplification (skeletonization) of the WDS. Then it trains an ANN model and finally it searches for the optimal solution with GA. Bene et al. (2010) also found the least-cost pump schedule using the neutral search technique with GA. The optimization was subject to the several constraints including the storage and source limitations, pump setting bounds, and power demand charges. They concluded that the neutral search technique outperforms the conventional GA models.
Although sophisticated methods have been used to achieve the least-cost solutions in the literature, in most of them the proposed models were applied to a small and hypothetical system. In reality the programmable logic controller (PLC) is commonly being used to control the pumps, valves, and reservoirs especially in the transmission pipelines. Almost in all of the mentioned papers, PLC and their effects were not incorporated to simplify the simulations. This can compromise the practicality of the proposed approaches. Another major issue which prevents these methods to be acceptable and applicable in the industry is that they use the pre-assigned time slots to simulate the pump on/off cycle. These issues are discussed in detail in Chapter 3.

2.1.4 WDS Rehabilitation

Water distribution system rehabilitation planning is defined as finding the best place, the best time, and the best option to rehabilitate and replace WDS components (e.g. pipes, pumps, tanks etc.) in order to achieve one or more objectives. This is subject to hydraulic, construction, time, and budgetary constraints. In other words, the network rehabilitation is concerned with choosing the optimal set of rehabilitation interventions that minimize multiple objectives. Quite often WDS rehabilitation focuses on the water main rehabilitation options (e.g. pipe replacement, duplication, lining, installing new pipes, and break repair). The total cost comprises the cost of pipe replacement, pipe lining, installing new pipes in the expansion areas, pipe break repair, pipe leakage, and energy costs for pumping to overcome static lift and energy losses in the system. The search for optimal rehabilitation interventions that minimize the cost is subject to a number of constraints. The availability of financial resources, materials and components, and hydraulic performance of the system are among these constraints. The most common objective in the rehabilitation problem is the cost which can be framed as follows.
Minimize \( C_t = \sum_{t=1}^{T} \sum_{p=1}^{P} PV \left( D_p^t + L_p^t + R_p^t + N_p^t + BRC_p^t + LWC_p^t \right) + \sum_{t=1}^{T} PV (E_t) \)  \hspace{1cm} (4)

Where, \( C_t \) is the total cost within the time horizon \( T \), \( t \) is the year, \( P \) is the number of the pipes in the network, \( p \) is the pipe index, \( PV() \) is the present value function, \( D_p^t \) is the cost of duplication for the pipe \( p \) at the year \( t \), \( L_p^t \) is the cost of lining for the pipe \( p \) at the year \( t \), \( R_p^t \) is the cost of replacement for the pipe \( p \) at the year \( t \), \( N_p^t \) is the cost of installing new pipes in the future growth area for the pipe \( p \) at the year \( t \), \( BRC_p^t \) is the break repair cost for the pipe \( p \) at the year \( t \), \( LWC_p^t \) is the lost water cost for the pipe \( p \) at the year \( t \), and \( E_t \) is the energy cost for the system at the year \( t \).

The water distribution network rehabilitation was initially formulated by Alperovits and Shamir (1977), Bhave (1978) and Deb (1976). These researchers framed network rehabilitation as a least-cost optimization problem. Shamir and Howard (1979) developed a procedure to schedule the pipe replacements based on the forecasted number of existing pipe breaks, replacement cost, and the discount rate. Walski (1985, 1986) and Walski and Pelliccia (1982) developed the least-cost criterion to replace the pipes with the break rates greater than the critical break rate. The least-cost criterion specifies that a pipe should be rehabilitated if the cost to rehabilitate is lower than the pumping cost without rehabilitation. They also concluded that the Shamir and Howard (1979) approach is useful to analyze the replacement of the entire group of pipes while their approach is more suitable in analyzing the economic replacement on pipe-by-pipe basis.

Building on the least-cost criterion, Day (1982) was the first to propose that WDS rehabilitation planning should be based on the realistic and up-to-date hydraulic information and not just based on the pipe age. Following this proposal, rehabilitation planning algorithms were developed to
link hydraulic solvers with optimization codes. The hydraulic solver continuously updates the optimization engine with up-to-date hydraulic data of the pipe performances in the system. Su et al. (1987) proposed the basic framework for the model that can find the least-cost design of WDS rehabilitation. This model was subjected to the mass and energy conservation, nodal pressure bounds, and reliability constraints. Reliability was defined as the probability of satisfying the demands and pressure bounds for various possible pipe failures (breaks). The hydraulic simulator, KYPIPE by Wood (1980), the reliability model based on the minimum cut set method, and the optimization engine based on the generalized reduced-gradient method were combined to find the optimal planning. This was the first time that a pipe break model and a hydraulic simulator were incorporated directly into the optimization engine to solve the WDS rehabilitation planning. Using the continuous pipe diameter rather than commercial discrete diameter was the biggest disadvantage of the proposed model.

Woodburn et al. (1987) and Lansey et al. (1992) proposed a model to determine the minimum cost solution in the WDS rehabilitation. The model was solved for the rehabilitation or replacement of the pipes in the system to meet the specific demand and pressure requirements while minimizing the costs. They included the cost of pipe replacement, pipe relining, expected repair cost, and energy cost in their approach. They used an algorithm called the operations research scheme to find the optimal solution. Instead of pipe diameter, the pipe length was used as the decision variable in the model therefore this model allowed for the rehabilitation and replacement of a portion of a pipe which is not realistic.

Kim and Mays (1994) continued the work by Lansey et al. (1992) and proposed a new methodology that can select the pipes to be rehabilitated or replaced in an existing WDS while the total rehabilitation and energy costs is minimized. They combined the KYPIPE hydraulic simulator with the generalized reduced gradient (GRG2) optimizer. The rehabilitation options
such as pipe replacement, lining, and do-nothing were included in the proposed model. The advantage of this model over the Lansey et al. (1992) model was that the integer variables algorithm was used to simulate the decisions for rehabilitation or replacement instead of pipe length which solved the partial pipe rehabilitation issue. The concept of Significant Index, SI, was introduced by Arulraj and Suresh (1995). SI is an optimality criterion which can be used in heuristic optimization models to prioritize rehabilitation activities for existing pipes or to design a new WDS. Schneiter et al. (1996) used the concept of capacity reliability (defined as the probability that a carrying capacity of the system meets the flow demand) and proposed a decision making platform for maintenance and rehabilitation of pipes in the network.

Kleiner et al. (1998a, 1998b) developed a rehabilitation framework based on the dynamic programming and partial and implicit enumeration schemes to minimize the cost of rehabilitation in the predefined time horizon. In their approach, network economics and hydraulic capacity were analyzed simultaneously. The Kleiner et al. model also considered the time-dependent deterioration of pipe structural integrity and pipe hydraulic capacity. Dandy and Engelhardt (2001) applied the genetic algorithm to minimize the present value of capital, repair and pipe damage costs for a real pipe network in Adelaide, Australia. They showed that GA could be a powerful tool to assist in planning for the WDS rehabilitation.

Lansey et al. (1989, 1992), Ejeta and Mays (2002), and Farmani et al. (2005) considered the system reliability as a separate objective in the multi-objective framework. Farmani et al. (2005) investigated the trade-off characteristics between the total cost and reliability of WDSs. A wide range of decision variables including pipe rehabilitation decisions, tanks sizing and setting, and pump operation schedules were considered in their approach and the model was applied to the Anytown benchmark network. The costs include the capital cost of pipes and tanks, and present value of the energy during the specific period. The resilience index (a surrogate measure for the
network reliability) was considered as the second objective. They concluded that the optimal solution on the payoff curve shows a poor performance under random pipe failure or pump being out of service.

Alvisi and Franchini (2006) proposed a procedure based on the multi-objective GA to find the near optimal rehabilitation planning. The first objective was to minimize the overall cost of the repair and or replacing pipes and the second objective was to maximize the hydraulic performance of the network. They also considered the annual budget constraint. A head-driven hydraulic simulator was linked to a GA engine to simulate the various hydraulic and pipe break scenarios. They concluded that the multi-objective GA has the potential to be a useful tool for water main rehabilitation scheduling.

Jayaram and Srinivasan (2008) considered the life-cycle cost of pipe rehabilitation in a multi-objective GA framework to minimize the cost and maximize the hydraulic performance of a WDS. The life-cycle costs included the initial cost of the pipes, the pipe replacement cost, cleaning and lining cost, break repair cost, and the salvage value of the replaced pipes. A modification of the resilience index was used to maximize the reliability. The results indicated that the modified resilience index is a good indicator of the uncertainty handling ability of the system. Dridi et al. (2008) used and compared several evolutionary optimization techniques including IGA, NPGA-II, and NSGA-II to schedule the optimal water pipe renewal for short planning periods. Their results confirmed that using evolutionary algorithms could be useful to solve the pipe renewal scheduling problem. In particular, they recommended the use of NSGA-II to optimize large networks.

Nafi and Kleiner (2010 and 2011) incorporated the asset management strategies into a model which optimized the timing of pipe renewal in a WDS. They considered the discounts that
account for the adjacency of infrastructure works to the newly installed pipes and volume discounts on large quantities of purchased pipe for installation in networks. The Nafi and Kleiner (2010) optimization model minimized cost that included the pipe replacement and break repair and maximizes the usage of the available budget. The proposed model does not account for pipe roughness growth and leakage which often drives the search process since the operation cost is often the most significant component of the total cost.

The main rehabilitation decision option in the literature is pipe replacement and in rare cases pipe lining. This is mainly done to simplify the problem. In reality a full range of rehabilitation options for pipes including pipe duplication, replacement, various lining techniques, and installing new pipes in future growth areas are considered by utility managers. The lack of a comprehensive range of rehabilitation options in the proposed models sacrifices the practicality of the approach. There are several other assumptions in the previous approaches to simplify the complexity of the problem which compromise the outcomes. These assumptions are further discussed in Chapter 5.

2.2 Incorporating economic measures to mitigate GHG emission in the problem formulation

In recent years, public environmental awareness has increased. This is due to the fact that climate change poses a serious threat to mankind (Erwin et al. 2012). Governments of many developed and developing countries have started campaigns to mitigate GHG emission, which is the main cause of climate change. Financial tools are considered as an effective measure to mitigate GHG emission consequences (Stern et al. 2006). Carbon tax, cap-and-trade system, and discounting are various financial instruments that have been proposed in the literature to control GHG emissions. As mentioned in Chapter 1, in the carbon tax approach, the governments levy tax on the GHG emissions while in cap-and-trade system the governments issue a permit to each industry section,
allowing them to produce a specific amount of GHG emissions. If the permit holder’s emission exceeds the permitted limit, the holder should buy the extra permit from those who sell their permit in the market.

Taxing and cap-and-trade systems potentially can increase the electricity cost directly. Governments also use indirect methods to reduce the GHG emissions through controlling social discount rate. The social discount rate (SDR) is the minimum real rate of return that public projects must earn if they are to be worthwhile undertakings (Boardman et al. 2008). SDR has a significant impact on the projects’ economic analysis, especially in the projects with long-life and carbon footprints. If SDR is set to a high percentage, the effect of future costs would decrease in the economic analysis and vice versa. Since the energy cost and the extra costs from tax or cap-and-trade system are a part of the annual costs in water distribution projects, therefore SDR influences them. The GHG emission cost could be formulated as an extra term in equations (1) to (4). In its most complicated form in WDS rehabilitation, equation (4) can be formulated as:

$$\text{Minimize}(C_i) = \sum_{t=1}^{T} \sum_{p=1}^{P} PV\left(D_p + L_p + R_p + N_p + BRC_p + LWC_p\right) + \sum_{t=1}^{T} PV\left(E_t + G_t\right)$$

(5)

In which $G_t$ is the GHG cost. Note that GHG terms for WDS design/expansion and operation are formulated in detail in Chapter 3 and 4.

Only very recently, environmental considerations have been included in the WDS design. Filion et al. (2004) were the first to include life-cycle-energy-analysis to quantify energy expenditure in the fabrication, use, and end-of-life of the pipes, in WDS. The proposed approach incorporated the environmental input-output life-cycle-analysis to quantify the energy required to manufacture pipes. They have combined the EPANET hydraulic model with a pipe aging model and exponential pipe break model to calculate the theoretical energy recovery in the use stage. Then the energy required to dispose and recycle pipes was formulated. The final model was applied to
the New York tunnel benchmark with various pipe replacement frequencies from 10 to 100 years. The pipe replacement period close to 50 years produced the lowest overall energy expenditure in all of the life stages.

Dandy et al. (2006 and 2008) were the first to incorporate sustainability as a key objective in WDS optimization. A multi-objective GA was used to identify the Pareto optimal trade-off between cost and total energy for a simple WDS design. The total energy included the embedded energy of the materials and consumed energy in the system operation, while the capital cost only included the cost of pipes. Wu et al. (2008 and 2010a) incorporated the GHG emissions as the second objective in a multi-objective optimization framework, based on GA to solve WDS design. The model was used to investigate the trade-off between the traditional minimum cost objective and an additional environmental objective of minimizing GHG emissions. The model was applied to a simple WDS. Results indicated that incorporating the GHG emissions as a key objective causes a significant trade-off between economic objective and environmental objective. They also concluded that the Pareto front is very sensitive to the discount rate.

Wu et al. (2010b) compared the use of single-objective and multi-objective approaches to investigate the trade-off between economic objectives and GHG emission. In Wu at al. (2010a) authors used GHG emissions as one objective while in the Wu et al. (2010b) paper GHG emissions were converted to GHG cost using the carbon tax model. This made it possible to investigate the environmental aspects of the WDS design in a single-objective framework. Two simple WDSs were analyzed. The results indicated that the single-objective approach produced less trade-off information between the GHG emission and system costs. They recommended the multi-objective approach to find the optimal WDSs design while accounting for the GHG emissions over the single-objective approach.
In another study Wu et al. (2012) investigated the effects of considering variable speed pumps (VPS) and fixed speed pumps (FSP) in water transmission systems to reduce the energy consumption and GHG emission. A pump power estimation method was developed and used to incorporate the VSP. The proposed method was combined with a multi-objective optimization framework to minimize the total cost and GHG emissions. They indicated that the use of VSP could significantly save the operational costs and reduce GHG emissions.

With the exception of the Wu et al. (2012) paper, in all of the previous works in which environmental objectives had been considered, only the optimal WDS design was solved. The effects of considering the GHG emission mitigation scenarios on the water distribution system expansion, operation, and rehabilitation have not been investigated yet. Moreover the proposed models were applied on hypothetical simplified WDSs. Both of these issues are the main focus of this research.

It should be noted that this research attempts to see the direct consequences of the GHG mitigation policies on the design, expansion, operation, and rehabilitation of WDS through increasing the energy costs incurred by the GHG tax. Theoretically increasing the energy cost has the potential to increase the water cost leading to the water demand reduction. The demand reduction itself will reduce the energy consumption which decreases GHG emissions. Due to the lack of data and studies in this context, the impacts of GHG mitigation policies on the demand reduction are not investigated in this research.
2.3 GA-Based Single- and Multi-Objective Optimization

2.3.1 Introduction to the GA

Genetic Algorithms (GAs) are adaptive heuristic search algorithms based on evolutionary ideas about the natural selection and genetics inspired by Darwin’s theory of evolution. GAs were developed by John Holland (Goldberg 1989) and they continue to be one of the most successful evolutionary algorithms in recent years. GAs start with generating a group of random solutions for the problem. Each solution is called a String or a Chromosome and a group of these solutions is called a Generation or Population. Each solution is the combination of decision variables (Genes) required to solve the problem. Depending on the type of decision variables considered, each gene could be a binary number, an integer number, or a real number and a chromosome could contain one or a combination of various types of genes. Assume a hypothetical problem in which the goal is to find the optimal pipe diameters for a WDS consisting of 10 pipes and the objective is to minimize the construction cost. Therefore each solution (String) consists of 10 decision variables and holds together an array of numbers (Genes). GA produces several of these solutions randomly (Population) and then evaluates each solution to see if it satisfies the problem’s constraints. The GA then calculates the objective value for each solution. In the WDS design example, the constraints could be the minimum and maximum pressure in each node or the velocity in the pipes and the objective value is the cost of each solution. The value of the objective function can be used as one of the indicators of the fitness of each solution in the problem. The objective value generally is combined with the penalty value which represents whether the solution satisfies all of the constraints or not. The combination of the objective value and penalty value is called the fitness value. The way these two variables are combined is called the fitness function.
The evaluation of the objective functions and constraints in a GA depends on the problem itself. In the WDS least-cost design, the objective function is the total cost of the pipes but to evaluate the constraints the WDS should be simulated with a network hydraulic solver (e.g. EPANET hydraulic model by Rossman 1994). In the ordinary GA, if a solution does not satisfy its constraints, a penalty coefficient would be applied to the objective value. For instance if the pressure in a node was higher than the allowable pressure, the objective value would be multiplied by a coefficient to increase the cost of the solution.

![Figure 2.1 The typical genetic algorithm flowchart](image-url)

*Figure 2.1 The typical genetic algorithm flowchart*
GAs mimic nature where the fittest animals (those most adapted to their environment) have the highest chance to survive, mate, and pass their genes to their offspring. Therefore in GAs, the solutions with the highest fitness values “survive” and can pass on their genes to the next generation of solutions. The selection function, crossing and mutation follow the “survival of the fittest” concept in nature. These functions are also called GA operators. In the WDS design analogy, the fittest solution is the one that satisfies all the design constraints and has the least-cost. This solution has greater opportunity to mate with other solutions and hence it has a higher chance to pass its genes to the next generation of solutions. Producing a new generation from the old generation continues until the stopping criterion is satisfied. This procedure is illustrated in the Figure 2.1. The most common stopping criterion is based on the number of generations. There are other types of stopping criteria such as the execution time, the variance of the objective values, and using scalar quantities such as the hyper-volume.

2.3.2 GA operators

As mentioned in the last section, the selection, crossover and mutation are the three GA operators with equivalents in nature. Various techniques have been reported for these operators in the literature. The first operator is the selection operator. The goal of this operator is to increase the probability of selecting suitable solutions (solution with a high fitness value) to convey their genes to the next generation of solutions. The simplest form of selection operator is the roulette wheel in which the smaller numbers have more space (slots). In GA, these numbers are the solutions with better objectives. There are other methods such as the elitist selection and tournament selection which are discussed in detail in the next section. In the general form of GA, a mating pool with the same number of solutions as the parent population is created from the
selected solutions and the solutions are crossed in the next step to produce the offspring generation.

The second operator is the crossover operator which copies the mating in nature. The crossing combines two solutions (P1 and P2 in Figure 2.2) which previously have been identified for having desired characteristics (e.g. solutions with lower costs) and produces two new offspring (C1 and C2 in Figure 2.2). There is no guarantee that the desired genes (characteristics) are passed on to the offspring but since better solutions have a higher chance to mate therefore those suitable genes have more chance to be passed on. In the simple crossover of chromosomes, solutions are divided in two or more parts and the parts between two chromosomes are interchanged. The points where each chromosome is broken are decided randomly by chance or by the user. Also the probability of the successful crossover is chosen by the user.

In the nature, evolution occurs as a result of gene crossing and mutation. The third operator in GA is the Mutation which introduces the diversity to the population. It prevents the GA search from getting trapping into local optima. The simplest form of the Mutation operator changes genes in each chromosome randomly. The probability of a successful Mutation is defined by the user and it is generally a small probability. Figure 2.3 illustrates the mutation operator.
2.3.3 Single-Objective GA, Elitist GA
Whenever there is only one objective function in the optimization process, the problem is called single-objective. This objective could minimize or maximize the objective value. For instance traditionally the costs should be minimized and objective such as the reliability should be maximized in the WDS design/expansion, operation, and rehabilitation. There are several GAs designed to solve these type of problems. Among them the elitist GA (EGA) was proven to outperform others (Majumdar and Bhunia 2007). EGAs are based on standard GAs, unlike standard GAs, EGAs copy the fittest chromosomes over to the next generation (elitism) and generate the remaining solutions by the crossing and mutation. Retaining the fittest chromosomes and copying them to the next generation increases the performance of the EGA search process (Bhandari et al. 1996; Majumdar and Bhunia 2007).

2.3.4 Multi-Objective GA, NSGA-II
Most engineering problems in the real world have multiple objectives which need to be satisfied simultaneously. For instance the reliability in WDS problems should be maximized, while the cost should be minimized. GA by its nature is a single-objective optimization framework. The primary approach to solve multi-objective problems is to convert multi-objective problems to single-objective problems. Approaches such as the Weighted Sum method, Weighted Metric method, $\varepsilon$-constraint algorithm, Value Function method and Goal programming techniques
follow this principle (Deb 2002). Several problems are attributed to these methods for instance
they are not able to search the true objective space (Singh et al. 2003). They do not provide the
trade-off between the objectives (Deb 2002). A real multi-objective GA should be used to solve
the WDS problems with more than one objective. Probably the first real multi-objective GA is the
Vector Evaluated GA (VEGA) by Schaffer (1985). In 1992 the weighted based GA was
introduced by Hajela and Lin (1992). The non-dominated Sorting GA (NSGA) was first
introduced by Srivinas and Deb (1994) and the second version was introduced by Deb et al.
(2002). Since 2002, NSGA-II has been widely used by researchers in various fields. In the WDS
analysis field it has been used by Dridi et al. (2008), Dandy et al. (2008), Wu et al (2010a), Nafi
and Kleiner (2010).

NSGA-II has two important characteristics: 1) It does not use the penalty function, and 2) It is
less computationally expensive than most other multi-objective optimization methods. NSGA-II
employs tournament selection to search for non-dominated solutions. From a population of N
parent chromosomes and N offspring chromosomes (found by applying crossover and mutation
operators), NSGA-II combines parent and offspring populations to form a population of 2N
chromosomes. The NSGA-II then sorts all 2N chromosomes in a new generation and assigns a
rank to each of them based on their objective function values (or error value). To generate a new
population with N chromosomes, NSGA-II selects all chromosomes in the first rank and then
adds all chromosomes in the second rank, and so on. This is continued by adding chromosomes
that belong to the next rank until the total number of chromosomes selected is greater than N. A
crowding distance (CD) parameter is used to compare between chromosomes with the same rank
in the sub-set of fit chromosomes. (CD represents the density of chromosomes that surround a
particular solution.) All of the multi-objective optimization problems in this research were solved
with the non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2002).
2.3.5 Penalty Functions

NSGA-II does not have a penalty function while EGA needs a penalty function to lower the likelihood of selecting undesirable solutions. Penalty value has been calculated from (6) for all of the scenarios in the following chapters where EGA has been used.

\[ P_{ty} = C \times Err \]  

(6)

In which \( P_{ty} \) is the penalty value that would be added to the objective value. \( C \) is the constant coefficient, and \( Err \) is the calculated error for the solution.

2.4 OptiNET

For the purpose of this research, the optimization framework called OptiNET is developed which can solve the single- and multi-objective WDS problems. Various versions of OptiNET are able to solve the WDS design/expansion, operation, and rehabilitation problems. It uses the EGA to solve single-objective problems and the NSGA-II to solve multi-objective problems. The EpaNET is linked to OptiNET to hydraulically simulate WDSs. OptiNET also includes the pipe roughness growth models, pipe break forecasting model, pipe leakage growth model, financial models to calculate the objectives, demand growth model, asset management modules and a graphical user interface (GUI). Figure 2.4 illustrates the OptiNET graphical user interface.

All of the interfaces in the GUI and the computational subroutines were developed using the C# programming language in Visual Studio 2008 and 2010. EPANET2.0 toolkit is also linked to the OptiNET by C# and compiled for the 64 bit environment. Solving the optimal water main rehabilitation problem for a complex, real-world water distribution system requires a tremendous amount of computer power. To address this challenge, two parallel computing techniques (the Task Parallel Library (TPL), and Massage Passing Interface (MPI)) were employed. The proposed techniques increased the speed of the optimization procedure dramatically. On the cluster framework (the 120 core machine running windows HPC server 2008R2) designed and
built to run OptiNET, it was able to reduce the execution time by a factor of 72. The application of parallel processing and its details are published in the Water Distribution System Analysis (WDSA) 2012 proceedings (Roshani and Filion 2012a).

**Figure 2.4 The OptiNET graphical user interface.**

**2.4.1 Asset Management and Model Validation**

The NSGA-II optimization engine in OptiNET was validated using all of the benchmark problems mentioned in the Deb et al. (2002). The benchmark problems detail and the model outcomes are included in the Appendix A. The WDS subroutines were tested and validated using the benchmark networks in Simpson et al. (1994). No benchmark is available on the WDS rehabilitation in the literature which contains all of the sub-models. As mentioned in the last section, the OptiNET contains several models, to test the framework and to make sure that all of its sub-routines are linked correctly and worked properly. Then OptiNET was applied to the real world case study, The Fairfield WDS, and various asset management strategies were incorporated
to the problem definition. The results were examined with manual calculation to find any kind of calculation errors or unrealistic outcomes. The results are submitted as a manuscript to ASCE Journal of Water Resource Planning and Management (Roshani and Filion 2012b).

2.5 Research Contributions

This section discusses the contributions of the four journal publications presented in the subsequent chapters (3, 4, 5, and 6). The overall aim of this study is to investigate the effects of considering the GHG mitigation strategies on the WDS optimization problems including the operation, design/expansion, and rehabilitation planning via the single- and multi-objective approaches. In order to achieve this, eight sub-objectives were identified in the first chapter. Each publication covers part of these sub-objectives. Figure 2.5 illustrates the relevance of four journal publications and their contents to eight sub-objectives of this research.
OptiNET

1. Optimization Framework
2. Gene Coding Techniques
3. Pipe Aging Models

4. WDS Pump Scheduling
5. WDS Design/Expansion
6. Asset Management Strategies
7. WDS Rehabilitation
8. Sensitivity Analysis

Figure 2.5 Contribution of the four journal papers presented in this thesis in relation to the thesis objectives
2.5.1 Publication 1: “Impact of Uncertain Discount Rates and Carbon Pricing on the Optimal Design and Operation of the KamalSaleh Water Transmission System”

This publication describes and formulates the WDS operation in the single- and multi-objective frameworks (Objective # 1) while it accounts for the carbon mitigation strategies. It explores the trade-off between the cost of reservoir construction and the cost of electricity consumed to pump water plus the extra cost of the GHG emission tax (Objective 4). Transmission pipe lines are often designed for a long life (e.g. 50 years and longer). Therefore the operational cost of these structures will occur over a long period of time while most of the construction cost happens at the beginning year. A present value analysis (PVA) is required to investigate and compare the time performance of the operational costs with the capital costs. The discount rate (DR) plays an important role in calculating the net present value of the costs. Since GHG tax is part of the operational cost which happens in a long time therefore DR can diminish or highlight its effects. Additionally, the actual cost of GHG tax could effect the design and GHG emission. The first contribution of this publication is to investigate the effects of uncertain discount rate and GHG cost on the GHG mass, reservoirs design and setting, and the pump scheduling.

The second major contribution of this publication is that the proposed model is applied on the real world water transmission system with 3 pumping stations (over 16 pumps), 6 reservoirs and a SCADA system which controls the entire line. All of the previous approaches in this field were applied on hypothetical and simplified systems. This compromises the practicality of the previous approaches and limits the outcomes to the simple systems. In this research all of the components of a real-world system including the supervisory control and data acquisition were simulated.

The third major contribution is the development of a new methodology to encode the pump scheduling problem with the genetic algorithm (Objective #2). In the traditional approach each gene represents one hour of the pump simulation time. If the gene value equals 1, it means the
pump should stay on for one hour and if it is 0, it means the pump should be off for one hour. This approach has two major problems; it needs at least 24 genes to simulate one pump in 24 hours period which is the common simulation time. And it limits the minimum time slots to one hour which is not realistic. The proposed gene encoding approach eliminates both of these problems. The detail about the proposed methodology is included in the Chapter 3.

2.5.2 Publication 2: “Evaluating the Impact of Climate Change Mitigation Strategies on the Optimal Design and Expansion of the Fairfield, Ontario Water Network: A Canadian Case Study”

The second publication formulates the WDS design/expansion under climate change mitigation strategies in a single-objective framework (Objective #5). The major contribution of this publication is to use optimization approach in a parametric analysis to explore the impacts of discounting and carbon pricing on the GHG emission reduction in the WDS design and expansion for the first time.

For the first time ever the real proposed policies on the time-varying carbon pricing and time-varying GHG emission factors were considered in the evaluation procedure for the design and expansion of a relatively complex system. Additionally, the effectiveness of the GHG mitigation strategies was examined in a real network that is not otherwise accessible through case studies of simplistic systems.

Pipe construction materials have various surface roughness and they follow different roughness growth rates which can effect the energy requirement for pumping water into the system. Another major contribution of the second publication is to investigate and compare the effects of various pipe materials (e.g. the cement-mortar ductile iron and polyvinyl chloride pipe materials) on the energy and GHG mass reduction in WDSs.
In the previous works mainly the pipe replacement were considered to update the current WDSs and rarely the pipe cleaning and lining was considered. In reality a wider range of options are used by utility managers. The proposed model includes all of the common options to update the system including the pipe replacement, pipe cleaning and lining, and pipe duplication. It also considers new pipe installations for the future growth areas which make the problem more complicated.

2.5.3 Publication 3: “Event-Based Approach to Optimize the Timing of Water Main Rehabilitation While Considering Asset Management Strategies”

The main goal of publication 3 is to develop and examine the required multi-objective framework to find the optimal WDS rehabilitation plan (Objective #1). The WDS rehabilitation planning is the most complicated WDS optimization problem. This is because the decisions are time-dependent and pipe aging processes should be incorporated in the framework. The proposed framework includes 5 different models: the optimization engine, pipe roughness model, pipe break model, pipe leak model, and hydraulic simulator (Objective #3). This is for the first time that all of these models are considered simultaneously to find the optimal WDS rehabilitation plan. A trade-off between the capital costs of network rehabilitation and the network operating costs were explored. The capital costs included the pipe replacement costs, lining costs, duplication costs, and installing new pipes costs, while the operational costs accounted for the break repair cost, energy cost, and water loss cost. The proposed model was applied to the Fairfield WDS which is a fairly complicated system.

The second major contribution of the Publication 3 is that it proposes a new approach for gene coding to solve the WDS rehabilitation (Objective #2). In the traditional approach each year of the project life span is modeled by the one gene for instance to model one pipe in its life span of 50 years, 50 genes are required. Note that if the pipe duplication is among the decision options,
the number of the required genes should be doubled to account for the second pipe rehabilitation planning. This causes several problems including the memory and computational issues. The proposed approach reduces the number of the genes by 80 percents. It allows including all of the rehabilitation options in the decision domain. Again this is for the first time that the pipe replacement, pipe lining, pipe duplication, and installing new pipes in the future growth areas are considered in the decision domain of the WDS rehabilitation planning.

The third major contribution of this publication is that it includes asset management strategies such as the adjacency to public works discount, quantity discount, and annual budgetary limits (Objective #6). Applying these strategies can potentially reduce the construction costs. It also investigates the effects of considering these strategies on the distribution of the rehabilitation decisions over the time and location. Finally the last major contribution of this publication is the sensitivity analysis of the model (Objective #8). Variables such as the forecasted water demand, roughness growth rate, initial leak rate, leak growth rate, initial and break growth rate are included in the sensitivity analysis.

2.5.4 Publication 4: “Water Distribution System Rehabilitation under Climate Change Mitigation Scenarios in Canada”

Publication 4 deals with the effects and consequences of considering the GHG mitigation scenarios in the WDS rehabilitation planning (Objective #7). Formulating the WDS rehabilitation planning under the climate change strategies for the first time ever is this publication’s most important contribution. Secondly, it explores the effects of the uncertain GHG tax and discount rates not only on the energy consumption and GHG emission but also on parameters such as the water loss costs, break repair cost, and the distribution of the decision options. It investigates the trade-off between the capital cost minimization and operational cost minimization. The proposed model is applied to the real Fairfield WDS in Amherstview, Ontario, and it studies the effects of
various GHG pricing and discount rate on the shape and location of the optimal Pareto fronts. Finally an extensive sensitivity analysis is performed on the input variables (Objective #8).

Note that the multi-objective framework that has been used in this study is also unique. It accounts for the fullest range of decision variables (e.g. the pipe duplication, replacement, relining, and installing new pipes). It applies pipe aging models such as the roughness growth, leakage, and pipe break to fully simulate the aging effects on the pipes performance in the system.

2.6 References


Chapter 3

3.1 Abstract
Carbon tax and carbon cap-and-trade frameworks being proposed in international jurisdictions stand to change the manner in which water utilities plan, design, and manage water systems. In this paper, single-objective and multi-objective optimization approaches are applied to the design of the KamalSaleh water transmission pipeline in KamalSaleh, Iran to examine the impact of a carbon tax and discount rates on the optimization of the system. Single-objective results indicate that a carbon tax and discount rate have a noticeable impact on capital costs and the level of installed reservoir storage in the system, and produce only small reductions in greenhouse gas emissions from electricity use from pumping. This is owing to the high static head that dominates the energy requirements of the KamalSaleh system and that is unaffected by discount rate and the carbon tax. Multi-objective optimization results indicate that decreasing discount rate and increasing the carbon tax increases the steepness of the Pareto front where modest investments in reservoir storage produce significant reductions in operational cost.

Keywords: water transmission system, discount rate, carbon tax, sustainability, energy use, greenhouse gas emissions, design, optimization, operation.
3.2 Introduction

Throughout the world, the water sector is a heavy consumer of electricity for raw water pumping in transmission systems and for pumping drinking water in urban distribution networks. One estimate indicates that the energy used to pump, and heat water is approximately 13% of all US electricity generation (Griffiths-Sattenspiel and Wilson 2009). The latest International Energy Agency monthly report indicates that 62% of electricity is generated through the combustion of fossil-fuels (e.g., coal, natural gas) (IEA 2012) which releases greenhouse gases (GHGs) such as carbon dioxide into the atmosphere. Clarke et al. (2009) estimated that water provision and water heating account for 6% of GHGs emitted in the UK. For this reason, many countries such as the United Kingdom, Australia, Canada, and Iran are planning, or already have begun, to use economic instruments such as levying carbon taxes, introducing carbon cap-and-trade systems, and using economic discounting in project planning to encourage large economic sectors–including the water sector–to reduce their GHG emissions and mitigate future damages caused by climate change.

3.2.1 Economic Instruments to Mitigate GHG Emissions

A carbon tax and economic discounting have been proposed by researchers and economists to mitigate the climate change effects of GHG emissions. Under a carbon tax structure, a government can levy a tax on a sector’s GHG emissions to encourage it to reduce its emissions. Since 2009, the provincial Government of British Colombia in Canada has adopted a carbon tax on gasoline fuel (Ministry of Small Business and Revenue 2008). Economic discounting is another instrument being considered to encourage sectors to reduce their GHG emissions. Note that the discounting can affect the project with or without a carbon tax. The social discount rate (SDR) is defined as the minimum real rate of return that public projects must earn if they are to be worthwhile undertakings (Boardman et al. 2008). The SDR can have a significant impact on
the economic analysis of a project especially for long-term projects with climate change implications (Nordhaus 1991, Cline 1992). For example, social discount rates being proposed by Stern et al. (2007) and others would give greater weighting to GHG costs incurred in the future and thus have the potential to lower GHG emissions linked to the construction and operation of public infrastructure projects such as drinking water systems.

Recent research has begun to investigate how a carbon tax and social discounting stand to change the way water utilities manage system design and make improvements in aging systems to mitigate their GHG emissions (Roshani et al. 2012a and Wu et al. 2010a). The key questions here are: (1) How will a carbon tax and social discounting affect design and operation decisions made by water utilities for their systems?, and (2) How will a carbon tax and social discounting affect the energy use and greenhouse gas emissions generated by water distribution networks? These questions are particularly relevant in large water transfer projects that typically have large pumping and operating requirements over service lives that span 50 to 100 years. Since water is heavy (~1,000 kg/m$^3$) and systems are in operation for a long period of time, energy use and therefore GHG emissions are often largest in the operational stage of a system. In these projects, sizing and placement of storage reservoirs can have an important influence on pumping operations (time and number of pumps being used) as well as on pump control and pumping energy use. Given the dominance of the operational stage, the embodied energy associated with the construction of reservoirs and fabrication of pipes was not included in the case study of the present paper.

Iran is undertaking a substantial expansion of its water infrastructure in large to mid-sized cities. The KamalSaleh water transmission pipeline, the subject of the case study presented in this paper, delivers water to the mid-sized city of Arak, which is located in the geographic centre of Iran. The KamalSaleh system is relied upon to supply water to sustain Arak’s rapid growth in
population and industry. Iran is also part of the international movement toward decreasing GHG emissions to address climate change. There is a growing interest to examine the impact of carbon mitigating strategies on the energy use and GHG emissions generated by the domestic water industry in Iran.

3.2.2 Previous Research in the Optimization of Sustainable Water Distribution Networks

Recently, a number of researchers have developed both single-objective and multi-objective optimization programs that incorporate the environmental impacts of upgrading and operating water distribution networks. Dandy et al. (2006) developed a multi-objective optimization program that incorporates sustainability objectives of whole-of-life-cycle costs, energy use, greenhouse gas emissions, and resource consumption. The optimization program was applied to a real network in Australia, where the least-cost design was compared with the ‘environmentally sustainable’ design. The ‘sustainable’ design was found to have a lower cost, a reduced rate of PVC material and energy use, and lower levels of greenhouse gas emissions. Later, Dandy et al. (2008) developed a multi-objective optimization program that incorporates the objectives of cost and embodied energy of pipes. The multi-objective program was applied to a hypothetical test network to solve both the single-objective and multi-objective problems. In the single-objective problem, the authors found the minimum-cost solution to comprise of PVC-M (modified PVC) pipe with a low unit cost, and the minimum-energy solution to comprise a mixture of PVC-M and PVC-U (unplasticized PVC) pipe with low embodied energy values. The multi-objective analysis indicated a trade-off between the cost and embodied energy objectives.

Wu et al. (2010a) developed a multi-objective optimization program that incorporates a carbon tax on GHG emissions linked to the fabrication and operation of water distribution networks. Their multi-objective optimization program was used to examine the impact of discount rates and
a carbon tax on the cost and GHG emissions associated with Pareto-optimal solutions. The results of two single-objective network examples indicated that for low discount rates and a high carbon tax, the optimization program chose larger pipes to reduce energy use and GHG emissions in the operation stage.

Wu et al. (2010b) compared the use of single-objective and multi-objective optimization approaches to account for GHG emissions in water distribution networks. Their analysis indicated that a multi-objective approach was better able to account for the trade-off between costs and GHG emissions than the single-objective approach.

Roshani et al. (2012a) developed a single-objective optimization framework to assess the effects of proposed Canadian climate change mitigation change policies (lowering the discount rate and introducing a carbon tax) on cost, energy use, and GHG emissions in the design and expansion of the Fairfield water distribution network in Amherstview, Ontario, Canada. Their analysis indicated that the proposed discount rate and carbon tax had no significant influence on energy use and GHG emissions in the Fairfield system. This result was attributed to a number of factors that included: 1) adequate installed hydraulic capacity in the Fairfield system, 2) the use of a time-declining GHG emission intensity factor, and 3) the limited scope of the expansion problem.

Wu et al. (2010a and 2010b) examined the impact of discounting and a carbon tax on GHG emissions in the design of systems with fewer than 10 pipes. These previous studies focused on pipe sizing only and did not consider other factors such as pump scheduling and reservoir operation which might have a large impact on energy use and GHG emissions. While Roshani et al. (2012a) examined the impact of discounting and a carbon tax on GHG emissions in the more complex all-pipes Fairfield water network in Amherstview, Ontario, Canada, they too focused only on pipe sizing and did not consider pump scheduling and reservoir operations in any detail.
The difference in results reported by Wu et al. (2010a) and Roshani et al. (2012a) indicates that network complexity (number of pipes, tanks, reservoirs, and pumping stations) can potentially have an influence on the sensitivity of energy use and GHG emissions to changes in discount rate and carbon tax levels.

Wu et al. (2012a) incorporated variable-speed pumping into the design of new water transmission systems and combined it with optimization to minimize the costs and GHG emissions associated with pumping. The authors developed a generic pump power estimation method which uses a flow control valve (FCV) element in a network solver (EPANET2) and the false position method optimization approach. They applied their new approach to a simple water transmission system with a single pump and demonstrated that variable-speed pump control could decrease the cost and GHG emissions in a water transmission system.

Wu et al. (2012b) examined the sensitivity of optimal trade-off relationships between cost and GHG emissions to uncertainties in electricity generation and tariffs. The sensitivity analysis was performed on a simple water transmission system with a single pump. Their analysis suggested that uncertainty in electricity tariffs can have a significant effect on pumping costs but only a small effect on GHG emissions. Wu et al. also demonstrated that uncertainty in the GHG emission factor has no direct effect on the total cost of the system.

The overall objective of the research is to examine the impact of carbon mitigating strategies on the design and operation of the KamalSaleh water transmission system. The specific objectives of the paper are to examine the impact of a carbon tax and social discounting on: (1) the optimal design of regulation reservoirs and the optimization of pump operations in the KamalSaleh water transmission system, and (2) the cost, energy use, and greenhouse gas emissions generated by the KamalSaleh water transmission system. The real-world KamalSaleh water transmission pipeline
in Iran has a length of 79 km and comprises 3 submerged pumping stations, 3 dry pumping stations, and 6 regulation reservoirs. The paper’s objectives are achieved by way of a scenario analysis that examines the impact of discounting and a carbon tax on the design and operation of the KamalSaleh system in the next 50 years. In each scenario, the regulation reservoirs and pump operations are optimized and the reservoir construction cost, electricity cost, GHG cost, and the GHG mass generated in the KamalSaleh system are calculated. The optimization includes the decision variables for sizing reservoirs that included initial water level, minimum allowable water level, maximum allowable water level, and equivalent reservoir diameter. The decisions variables that related to the pumps included the pump on/off status and pump operation duration.

To the authors’ knowledge, the present study is the first ever to investigate the impact of a carbon tax and social discount rates on energy use and GHG emissions in a real, complex water transmission pipeline. Previous researchers have focused on examining the relationship between carbon mitigating strategies and energy use and GHG emissions in simplified water distribution or transmission systems with one pump and fewer than 10 pipes. The study builds on the work of Wu et al. (2010b) in making the following advancements: (1) development of a new pump scheduling optimization approach that can model a Programmable Logic Controller (PLC) system that simultaneously controls the water level and pumps; (2) development of a new gene-coding approach that reduces the length of each chromosome and the associated memory requirements; (3) consideration of a real, complex water transmission system that includes 16 pumps and 6 reservoirs.

The analysis is also novel since the on/off pump schedules are optimized in simulated time rather than being pre-assigned before the optimization is performed. The most challenging issue in simulating a real transmission pipeline is simulating it in a real time manner. This means the pump schedule should be agile enough to respond very quickly to external triggers (e.g., water
levels in reservoirs). In reality, systems are controlled by a PLC machine which can override pre-assigned pumping schedules. A fair simulation of a real system should simulate the PLC commands as well. The proposed approach is designed to fully simulate the realities of pump scheduling. It enables the model to schedule the pump status on the order of seconds (which is critical for heavy duty pumps due to the amount of water they pump and their high level of energy use). In the traditional approach, the time step is usually fixed at one hour and pumping schedules are pre-assigned to individual pumps and/or pumping stations. In the proposed approach, the pumping time schedule is coupled and controlled ultimately by a PLC machine which controls the pumps status based on water level and the rate of falling or raising in the reservoirs.

The chapter is structured as follows; The single-objective and multi-objective optimization frameworks developed in this paper are presented. Then the Kamalsaleh case study and the carbon mitigating scenarios are presented. Following this, the results of the scenario analysis are presented and the impact of a carbon tax and social discount rates on the design and operational decisions, cost, energy use, and greenhouse gases of the Kamalsaleh project are discussed.

3.3 Kamalsaleh Water Transmission: Single-objective and Multi-objective Optimization

The Kamalsaleh water transmission pipeline shown in Figure 3.1 conveys water over a distance of 79 km from the Kamalsaleh reservoir dam to the City of Arak in Iran (population 2,000,000). The pipeline consists of 3 pumping stations and 6 reservoirs. The 3 pressurized pipe segments between Pumping Station #1 (PS. 1) and Reservoir #3 (Res. 3) in Figure 3.1 have an average pipe diameter of 1,500 mm. The 3 pipe segments that drain by gravity between Reservoir #3 (Res. 3) and Reservoir #6 (Res. 6) in Figure 3.1 have an average pipe diameter of 1,200 mm.
Figure 3.1 Schematic of KamalSaleh water transmission system.
Pumping Station #1 has 4 submerged service pumps and 1 submerged back-up pump. Pumping Stations #2 and #3 are dry stations each with 6 service pumps and 1 back-up pump. The goal of the KamalSaleh optimization problem is to minimize the capital cost of building new reservoirs and to minimize the cost to operate the system that includes the electricity cost for pumping and the carbon tax levied on GHG emissions generated in the production of electricity for pumping.

In this paper, a single-objective approach was used to optimize the KamalSaleh system and to compare the capital and operational cost objectives across carbon mitigating scenarios. A multi-objective optimization approach was also used to examine trade-off relationships between the capital and operational cost objectives (Wu et al. 2010b). The mathematical definitions of the multi-objective and single-objective approaches are given below.

### 3.3.1 Multi-Objective Optimization Formulation

The multi-objective optimization seeks to minimize the two objectives of: (1) one-time cost of new reservoirs to regulate pumping operations along the KamalSaleh pipeline, and (2) the ongoing electricity cost and carbon tax levied on electricity used for pumping. The objective functions for reservoir cost (CC) and operational costs (OC) are defined in (1)-(2).

Minimize:

**Objective 1**

\[
\text{Minimize:} \quad \sum_{r=1}^{RR} [Vol_r \times ConsC] \quad (1)
\]

**Objective 2**

\[
\text{Minimize:} \quad OC = \sum_{pm=1}^{PMP} \left[ PV\left(\left(E_{pm}^{1st} \times PC\right)_{25, I_P}\right) + PV\left(\left(E_{pm}^{2nd} \times PC\right)_{25, I_P}\right) \right] + \\
\sum_{pm=1}^{PMP} \left[ PV\left(\left(GHG_{pm}^{1st} \times GC\right)_{25, I_G}\right) + PV\left(\left(GHG_{pm}^{2nd} \times GC\right)_{25, I_G}\right) \right] \quad (2)
\]

in which \( CC = \) capital cost of reservoirs ($); \( RR = \) number of reservoirs; \( Vol_r = \) reservoir volume (m³); \( ConsC = \) construction cost per cubic meter of reservoir ($100 / \text{m}^3$); \( OC = \) operational cost ($); \( PMP = \) number of pumps; \( PV(X, n, I) = \) present value of yearly payment.
X in n = 25 years at a discount rate of $I$; $I_e$ = discount rate used to discount electricity costs; $I_G$ = social discount rate used to discount GHG costs; $PC$ = price of electricity ($0.08 / kWh). The discount rate used for electricity relates to the cost of borrowing that would be typically found in the private sector.

![Figure 3.2 Diurnal patterns used for first and second 25-year periods in the KamalSaleh water transmission pipeline.](image)

The design horizon of the project is 50 years (Lar 2005a) and it is divided into two 25-year periods to more accurately calculate energy use driven by an increase in demand and an increase in pipe roughness over the 50-year period. Here, $E_{pm}^{1st}$ = average annual energy used by pump pm in the first 25-year period; $E_{pm}^{2nd}$ = average annual energy used by pump pm in the second 25-year period. In the first 25-year period, a single 24-h diurnal demand pattern (Figure 3.2) is used along with a single set of Hazen-Williams ‘C’ factors that correspond to new pipes at t = 0 in the KamalSaleh system (Table 3-1) (Lar 2005a). In the second 25-year period, diurnal demand
factors in the 24-h diurnal demand pattern are increased by 10% to reflect the projected 10% increase in water demand over this period in the KamalSaleh system (Lar 2005a) driven by population growth and new industrial developments in Arak.

It is also noted that Hazen-Williams ‘C’ factors are adjusted downwards with the pipe-aging model of Sharp and Walski (1988) to reflect pipe-aging at time \( t = 50 \) years which is then applied to the second 25-year period. Therefore for each solution, the optimization algorithm evaluates the objectives and constraints (described below) for a 24-h diurnal pattern and ‘C’ factors at time \( t = 0 \) that applies to the first 25-year period, and diurnal pattern and ‘C’ factors at time \( t = 50 \) years that applies to the second 25-year period. \( GHG_{pm}^{1st}, GHG_{pm}^{2nd} \) = average annual mass of GHGs generated in the production of electricity to operate pump \( pm \) at time \( t = 0 \) (first 25-year period) and time \( t = 50 \) years (second 25-year period) in the KamalSaleh system. The annual mass of GHGs generated in electricity production for pumping is calculated by multiplying the daily energy use by 365 days and the weighted-average GHG emission factor of 0.75 kg CO2 / kWh (IWRMC 2005). The energy used in pumping water in the KamalSaleh system project is sourced from the national electricity grid in Iran. Therefore the weighted average GHG emission factor corresponds to a fuel mix of gas, coal, hydropower, and complex cycle fuels in Iran. GC is the carbon tax on electricity used for pumping ($ / tonne CO2-e). In this paper, it is assumed that the carbon tax on electricity use is transferred from an energy utility (who generates the electricity) to a customer water utility through a price increase that incorporates the carbon tax.
Table 3-1 Hazen-Williams ‘C’ factors of transmission pipes in the KamalSaleh system in the first and second 25-year periods.

<table>
<thead>
<tr>
<th>Pipe Diameter</th>
<th>Hazen-Williams ‘C’ Factor</th>
<th>Years 0 – 25</th>
<th>Years 25 - 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td></td>
<td>120</td>
<td>112</td>
</tr>
<tr>
<td>1200</td>
<td></td>
<td>120</td>
<td>112</td>
</tr>
<tr>
<td>1500</td>
<td></td>
<td>120</td>
<td>113</td>
</tr>
</tbody>
</table>

The multi-objective framework seeks to find a set of Pareto-optimal solutions that minimize the two objective functions simultaneously. Maintenance costs for pipes, and pumps were not included in the analysis since they are nearly identical in all solutions. The estimations based on the Iranian Plan and Budget Office (IPBO 2010) show that reservoir maintenance costs account for less than 0.05% of overall costs and therefore were not included in the analysis. Further, end-of-life decommissioning costs were not considered due to lack of data to quantify them.

The decision variables in the capital cost objective function of Objective (1) are the minimum operating reservoir level, the maximum operating reservoir level, and the equivalent reservoir diameter. Together, minimum and maximum levels and diameter establish reservoir storage volume. The decision variables in the operating cost objective function of Objective (2) are pump status (on/off), and duration between pump switches. A description of pump operations is given in section 3.3.4.

3.3.2 Single-Objective Optimization Formulation

The single-objective optimization formulation incorporates a single-objective function that sums the one-time cost of new reservoirs with the ongoing operation cost of the system in (3)

Minimize:  \( TC = CC + OC \)  \hspace{1cm} (3)
where $TC$ is total cost (capital + operating costs, $). Unlike in the multi-objective framework that seeks to find a set of Pareto-optimal solutions that minimize the two objective functions, the single-objective approach seeks to find a single solution that minimizes the total cost objective function of the system.

A number of assumptions have been made in the analysis because of the lack of data on key parameters. A constant emission factor was adopted because of a lack of data on a time-declining emission factor that would reflect an increased adoption of green energy production technologies in the future. A constant GHG emission factor implies that green energy production technologies will not be adopted in the future and likely comprises an overestimation of the GHG emissions and carbon tax costs in the KamalSaleh system. The embodied energy use and greenhouse gas emissions linked to concrete reservoir construction have been estimated to account for less than 0.1% of GHG emission based on an emission factor for reinforced concrete (Sustainable Concrete Forum 2012) and can justifiably be excluded from the model.

3.3.3 Optimization Constraints

The KamalSaleh optimization problem (both single-objective and multi-objective) is subject to constraints on continuity at all nodes

$$\sum Q_{in} - \sum Q_{out} = Q_n$$

for all $n = 1, 2, 3, \ldots, NN$ nodes

where, $NN =$ number of nodes; $Q_{in}$ = pipe flow into node $n$; $Q_{out}$ = pipe flow out of node $n$; and $Q_n$ = external demand at node $n$. The network solver EPANET2 (Rossman 2000) is used to satisfy this constraint external to the optimization program. Pressure head at all nodes must be higher than the minimum allowable pressure and lower than the maximum allowable pressure under peak demand conditions.
\[ P_{n}^{\text{min}} \leq P_{n} \leq P_{n}^{\text{max}} \] for all \( n = 1, 2, 3, \ldots, \) NN nodes \( (5) \)

where \( P_{n} \) = pressure head at node \( n \), \( P_{n}^{\text{min}}, P_{n}^{\text{max}} \) = minimum and maximum allowable pressure heads at node \( n \). Pipes velocities must be higher than the minimum allowable velocity to ensure acceptable water age and water quality and lower than the maximum allowable to prevent pipe scouring during peak demand conditions

\[ V_{p}^{\text{min}} \leq V_{p} \leq V_{p}^{\text{max}} \] for all \( p = 1, 2, 3, \ldots, \) PP pipes \( (6) \)

Where \( V_{p} \) = fluid velocity in pipe \( p \), \( V_{p}^{\text{min}}, V_{p}^{\text{max}} \) = minimum and maximum allowable fluid velocities in pipe \( p \). Reservoir diameters must be between the maximum and minimum allowable diameters allowed by local site conditions

\[ D_{r}^{\text{min}} \leq D_{r} \leq D_{r}^{\text{max}} \] for all \( r = 1, 2, 3, \ldots, \) RR reservoirs \( (7) \)

where \( D_{r} \) = equivalent diameter of reservoir \( r \), \( D_{r}^{\text{min}}, D_{r}^{\text{max}} \) = minimum and maximum allowable equivalent diameter in reservoir \( r \). 

### 3.3.4 Reservoir and Pump Operation Constraints

To maintain the stability of water levels over an extended time period, the maximum difference between the initial water level and final water level over the 24-h diurnal periods that apply to the first and second 25-year periods should be less than 20 cm in each reservoir

\[ |W_{r}^{\text{init}} - W_{r}^{\text{final}}| \leq W_{r}^{\text{allowable}} \] for all \( r = 1, 2, 3, \ldots, \) RR reservoirs \( (8) \)

where \( W_{r}^{\text{init}} \) = initial water level in reservoir \( r \), \( W_{r}^{\text{final}} \) = final water level in reservoir \( r \), \( W_{r}^{\text{allowable}} \) = allowable water level difference in reservoir \( r \). Local practice stipulates that water level difference be no greater than 5% of reservoir height and on that basis a maximum water level difference of 20 cm was selected (IPBO 2003). Constraints are also placed on maximum and minimum water levels. The maximum operating water level is set to the overflow reservoir level minus a
freeboard height of 0.2 m to prevent overflow. Similarly, the minimum operating water level is set to the bottom of the reservoir level plus a freeboard height of 0.2 m to prevent complete draining of the reservoir (IPBO 2003).

\[
\begin{align*}
\text{Max}(WL_r) & \leq (R_r^{\text{max}} - FB) \quad \text{for all } r = 1, 2, 3, \ldots, \text{RR reservoirs} \\
\text{Min}(WL_r) & \geq (R_r^{\text{min}} + FB) \quad \text{for all } r = 1, 2, 3, \ldots, \text{RR reservoirs}
\end{align*}
\]

where \( \text{Max}(WL_r), \text{Min}(WL_r) \) = maximum and minimum water levels observed in reservoir \( r \) during 24-h diurnal periods, \( R_r^{\text{max}} \) = overflow height of reservoir \( r \), \( R_r^{\text{min}} \) = bottom of reservoir \( r \), \( FB \) = freeboard height.

Each pump may switch on and off fewer than or equal to 5 times per day of service, as suggested by the pump manufacturer

\[
\text{CN}_{pm} \leq \text{CN}_{pm}^{\text{allow}} \quad \text{for all } pm = 1, 2, 3, \ldots, \text{PMP pumps}
\]

where \( \text{CN}_{pm} \) = number of on/off cycles for pump \( pm \) per day of service, \( \text{CN}_{pm}^{\text{allow}} \) = maximum allowable number of on/off cycles for pump \( pm \) per day of service. To prevent overheating in the electromotor of the pumps, the amount of time between pump switches (from on to off and vice versa) should be greater than 1,800 seconds (30 minutes). This time period is based on the specific manufacturer recommendations.

The pump control logic is indicated in Figure 3.3. The operating state of a pump is controlled by the water level in the downstream reservoir. At each time step, the pump control unit checks the water level and the rate of filling/draining in the downstream reservoir. Based on the water level and the rate of filling/draining, the control unit turns on or shuts off the pump to ensure that the reservoir does not overflow or drain completely.
3.4 Gene Coding Scheme for Pump Scheduling

With a traditional approach, a 24-hour pumping scheduling would require 24 binary genes, where each gene represents the on/off status in each hour of the scheduling period. For a scheduling problem the size of the KamalSaleh system, decreasing the time step to less than an hour increases the number of required genes as well as the computational and memory requirements. A new gene coding scheme was used to circumvent this problem. In this scheme, each gene is assigned a serial location identifier to denote the on/off pump status and a real-valued number to denote the duration of the on/off status. For example, if the first gene is assigned a real value of
3,400 and the second gene is assigned a real value of 8,700, this means that the pump will be on for the first 3,400 s of the simulation and then will be shut off for the remaining 8,700 s of the simulation. The real values could also be set to zero to reduce the number of on/off cycles. The total number of genes in the proposed coding scheme equals $2 \times N_{\text{pm}}^{\text{max}}$. Since the KamalSaleh case study has 16 pumps each with 5 maximum allowable pump switches, a total of 80 genes are required to simulate the system. The new gene coding scheme reduces the number of required genes by at least 60% and it is independent of the length of time steps. With a variable time step length, the algorithm is able to simulate a realistic pump-switching scheme that is typical of systems like the KamalSaleh system that are controlled in a real-time manner.

### 3.4.1 Elitist Genetic Algorithm

Design solutions for the single-objective approach were generated with an elitist genetic algorithm (EGA). EGAs are based on standard GAs but, unlike standard GAs, EGAs copy the fittest chromosomes over to the next generation (elitism) and generate the remaining solutions by crossover and mutation operations. Retaining the fittest chromosomes and copying them to the next generation increases the performance of the EGA search process (Bhandari et al. 1996; Majumdar and Bhunia 2007). In the EGA, design solutions that violate any constraint are assigned a “penalty error” that is added to the objective function value in (3). The “penalty error” inflates the cost in the objective function and thus decreases the likelihood that these solutions are carried forth in the next generation of the GA search process.

### 3.4.2 Non-Dominated Sorting Genetic Algorithm (NSGA-II)

The multi-objective optimization problem was solved with the non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2002). The NSGA-II was used to find optimal reservoir sizes and pump-scheduling patterns in the KamalSaleh water transmission pipeline. NSGA-II has two
important characteristics: 1) It does not use fitness function evaluation, and 2) It is less computationally expensive than most other multi-objective optimization methods. NSGA-II employs elitism selection to search for non-dominated solutions. From a population of N parent chromosomes and N offspring chromosomes (found by applying crossover and mutation operators), NSGA-II combines parent and offspring populations to form a population of 2N chromosomes. The NSGA-II then sorts all 2N chromosomes in this new generation and assigns a rank to each of them based on their objective function value (or error value). To generate a new population with N chromosomes, NSGA-II selects all chromosomes in the first rank and then adds all chromosomes in the second rank, and so on. This is continued by adding chromosomes that belong to the next rank until the total number of chromosomes selected is greater than N. A crowding distance (CD) parameter is used to compare between chromosomes with the same rank in the sub-set of fit chromosomes. (CD represents the density of chromosomes that surround a particular solution.) The algorithm indicates how the selection operator in NSGA-II selects chromosomes in the successive generations (Deb et al. 2002). EPANET2 hydraulic solver (Rossman 2000) is used to evaluate constraints (4)-(6) and the hydraulic performance of the network under average day and peak demands.

3.5 Case Study: KamalSaleh Water Transmission Pipeline

The KamalSaleh transmission pipeline indicated in Figure 3.1 conveys water from the KamalSaleh reservoir dam to the City of Arak in Iran with a population of approximately 2,000,000. This pipeline has a maximum capacity of 2.46 m3/s and a total length of 78.4 km. The pipeline consists of 3 pumping stations and 6 reservoirs. The pipeline has 3 pressurized pipe segments with average pipe diameters of 1,500 mm and 3 gravity pipe segments with average pipe diameters of 1,200 mm, as indicated in Figure 3.1.
This pipeline was designed in the year 2000 and construction started in 2001. In the year 2005, four years after the start of construction, and when more than 80% of the pipes had been installed and all pumps had been purchased, construction was stopped and put on hold for 3 years. In August 2008, the client asked the consulting engineer to review the design of the reservoirs to minimize the total cost to project completion. The case study in this paper considers the post-construction sizing of the reservoir in the KamalSaleh system where pipe diameters and pump sizes have already been determined. The case study will focus on reservoir sizing and pump-schedule selection and their impacts on direct operating cost and GHG-related cost.

To control the flow in gravity pipe segments, all reservoirs are equipped with two needle valves connected to a PLC (Programmable Logic Controller) that open and close with varying water levels in the downstream reservoir. The first submerged pumping station (PS. 1) was constructed in a vertical shaft with a depth of 70 meters and with 4 service pumps and 1 spare pump with an average capacity of 650 L/s and average pumping head of 110 meters (Lar 2005a). The second and third pumping stations (PS. 2 and PS. 3) are dry stations and have 6 service pumps and 1 spare pump with an average capacity of 450 L/s with pumping heads ranging from 170 m to 190 m (Lar 2005a). Pumping heads, discharges, reservoir water levels, valve opening status, etc. are controlled by a SCADA (Supervisory Control And Data Acquisition) system located in the central control room in Arak city.
Table 3-2 GHG mass, GHG cost, electricity cost, reservoir construction cost, and total cost for a range of discounting and carbon tax scenarios in the single-objective optimization of the KamalSaleh system.

<table>
<thead>
<tr>
<th>Scenario No.</th>
<th>Disc. Rate (Elec)</th>
<th>Disc. Rate (GHG)</th>
<th>GHG Tax ($/tonne)</th>
<th>GHG Mass (kg/day)(1)</th>
<th>Total GHG Mass (tonne)(2)</th>
<th>GHG Cost ($M)(2)</th>
<th>Pumping Time (hours)</th>
<th>Elec. Cost ($M)</th>
<th>Reservoirs Cost (SM)</th>
<th>Volume (m³)</th>
<th>Total Cost ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8%</td>
<td>8%</td>
<td>0</td>
<td>71,639</td>
<td>74,739</td>
<td>1,335,703</td>
<td>0</td>
<td>248.0</td>
<td>109.6</td>
<td>6.1</td>
<td>61,484</td>
</tr>
<tr>
<td>2</td>
<td>4%</td>
<td>4%</td>
<td>0</td>
<td>67,460</td>
<td>75,922</td>
<td>1,308,364</td>
<td>0</td>
<td>243.1</td>
<td>195</td>
<td>7.2</td>
<td>71,602</td>
</tr>
<tr>
<td>3</td>
<td>1.4%</td>
<td>1.4%</td>
<td>0</td>
<td>68,578</td>
<td>74,160</td>
<td>1,302,477</td>
<td>0</td>
<td>243.3</td>
<td>329.1</td>
<td>8.4</td>
<td>83,551</td>
</tr>
<tr>
<td>4</td>
<td>0%</td>
<td>0%</td>
<td>0</td>
<td>65,962</td>
<td>76,384</td>
<td>1,298,903</td>
<td>0</td>
<td>242.0</td>
<td>466.4</td>
<td>8.6</td>
<td>86,255</td>
</tr>
<tr>
<td>5 (Status Quo)</td>
<td>8%</td>
<td>8%</td>
<td>0</td>
<td>69,226</td>
<td>74,779</td>
<td>1,314,048</td>
<td>44</td>
<td>245.9</td>
<td>109.7</td>
<td>6.2</td>
<td>62,116</td>
</tr>
<tr>
<td>6</td>
<td>4%</td>
<td>4%</td>
<td>0</td>
<td>67,272</td>
<td>75,490</td>
<td>1,302,707</td>
<td>219</td>
<td>245.0</td>
<td>109.5</td>
<td>7.2</td>
<td>72,358</td>
</tr>
<tr>
<td>7</td>
<td>8%</td>
<td>8%</td>
<td>0</td>
<td>68,365</td>
<td>72,741</td>
<td>1,287,597</td>
<td>789.7</td>
<td>245.9</td>
<td>109.7</td>
<td>8.3</td>
<td>82,724</td>
</tr>
<tr>
<td>8</td>
<td>8%</td>
<td>8%</td>
<td>0</td>
<td>68,954</td>
<td>75,291</td>
<td>1,316,240</td>
<td>10.1</td>
<td>246.6</td>
<td>108</td>
<td>5.9</td>
<td>59,363</td>
</tr>
<tr>
<td>9</td>
<td>8%</td>
<td>8%</td>
<td>0</td>
<td>67,502</td>
<td>76,529</td>
<td>1,314,289</td>
<td>46</td>
<td>247.9</td>
<td>109.7</td>
<td>6.7</td>
<td>66,864</td>
</tr>
<tr>
<td>10</td>
<td>8%</td>
<td>8%</td>
<td>0</td>
<td>68,145</td>
<td>73,403</td>
<td>1,291,629</td>
<td>294.8</td>
<td>248.5</td>
<td>109.7</td>
<td>6.8</td>
<td>68,210</td>
</tr>
<tr>
<td>11</td>
<td>0%</td>
<td>0%</td>
<td>0</td>
<td>67,954</td>
<td>74,884</td>
<td>1,303,392</td>
<td>43.9</td>
<td>244.6</td>
<td>195.4</td>
<td>7.8</td>
<td>78,239</td>
</tr>
<tr>
<td>12</td>
<td>4%</td>
<td>4%</td>
<td>0</td>
<td>69,441</td>
<td>73,029</td>
<td>1,300,039</td>
<td>215.9</td>
<td>241.6</td>
<td>193.9</td>
<td>8.2</td>
<td>81,954</td>
</tr>
<tr>
<td>13</td>
<td>4%</td>
<td>4%</td>
<td>0</td>
<td>68,234</td>
<td>74,835</td>
<td>1,305,503</td>
<td>18.4</td>
<td>242.6</td>
<td>195.9</td>
<td>7.2</td>
<td>71,622</td>
</tr>
<tr>
<td>14</td>
<td>4%</td>
<td>4%</td>
<td>0</td>
<td>67,588</td>
<td>75,229</td>
<td>1,303,204</td>
<td>89.4</td>
<td>238.3</td>
<td>190.6</td>
<td>8.4</td>
<td>83,596</td>
</tr>
<tr>
<td>15</td>
<td>1.4%</td>
<td>1.4%</td>
<td>0</td>
<td>67,421</td>
<td>74,177</td>
<td>1,292,084</td>
<td>218.5</td>
<td>243.8</td>
<td>330.2</td>
<td>9.2</td>
<td>92,331</td>
</tr>
<tr>
<td>16</td>
<td>1.4%</td>
<td>1.4%</td>
<td>0</td>
<td>67,471</td>
<td>74,543</td>
<td>1,295,878</td>
<td>154.8</td>
<td>246.3</td>
<td>330.3</td>
<td>8.8</td>
<td>88,050</td>
</tr>
<tr>
<td>17</td>
<td>0%</td>
<td>0%</td>
<td>0</td>
<td>65,287</td>
<td>75,615</td>
<td>1,285,738</td>
<td>789.9</td>
<td>248.5</td>
<td>468.1</td>
<td>9.2</td>
<td>91,670</td>
</tr>
</tbody>
</table>

(1) The change in GHG mass linked to the dynamic pumping head only was reported in this table.
(2) All costs are in million dollars.
3.6 Single-Objective Optimization Results

A total of 17 discounting and carbon tax scenarios were run with the single-objective EGA approach to examine the impact of low discount rates and a carbon tax on the design and operation of the KamalSaleh system in the next 50 years. In each scenario, a particular discount rate was combined with a carbon tax and the EGA was run to optimize the design and operation of the KamalSaleh system. For each discounting and carbon tax scenario, the reservoir construction cost, electricity cost, GHG cost and GHG mass generated in the KamalSaleh system are indicated in Table 3-2.

Both electricity and greenhouse gas emission costs were discounted with discount rates ranging between 8% and 0% as suggested by (Lar 2005b) and Stern et al. (2006). The discount rate used for electricity costs relates to the cost of borrowing which is typically found in the private sector. The social discount rate used to discount GHG costs is meant to include the potential environmental damages from climate change from a public sector project. Electricity and GHG costs have been discounted with different rates in some scenarios to investigate the effect of discount rate on electricity costs and GHG costs separately. A carbon tax ranging from $0 / tonne CO2-e to $180 / tonne CO2-e Tol (2005) was imposed on greenhouse gases linked to electricity generation for pumping.

The ‘status quo’ discounting and carbon tax policy corresponds to Scenario 1 in Table 3-2, where electricity and GHG costs were discounted at a rate of 8% and the carbon tax was set to $0 / tonne CO2-e. The most ambitious discounting and carbon tax policy is reflected in Scenario 17 where both electricity cost and GHG emission costs were discounted at a rate of 0% and the carbon tax was set to $180 / tonne CO2-e (Tol 2005).

It is noted that Table 3-2 and Table 3-3 report the GHG mass linked to electricity use to satisfy the dynamic pumping head requirements of the system. Since the GHG mass linked to the static
pumping head is unaffected by decisions concerning reservoir storage sizing and pumping scheduling, it was not included in these tables (although it was included in the optimization procedure).

3.6.1 Impact of Discount Rate on Optimal Design, Costs, Electricity Use, and GHG Emissions

The effect of decreasing discount rate on the optimization is investigated in Scenarios 1 through 4, where discount rate was lowered from 8% to 0% and the carbon tax was held fixed at the ‘status quo’ level of $0 / tonne CO2-e. In Table 3-2, total cost increases with decreasing discount rate since increased weighting is placed on recurring electricity costs. To reduce the operational costs the search process can either decrease the pumping time, increase the reservoir volume, or change the reservoir operation parameters including the allowable minimum and maximum water level. It is noted that a combination of these strategies was employed by the search process. Decreasing discount rate in Scenarios 1 through 4 forced the optimization algorithm to select solutions with more reservoir volume (from 61,000 m³ in Scenario 1 to 86,000 m³ in Scenario 4) to reduce ongoing pumping and electricity requirements and lower continuing electricity costs.

In Scenarios 1 through 4, discount rate has little effect on pumping time. For instance, total pumping time in the status quo scenario (8% discount rate) is 248 hours, while in Scenario 4 (0% discount rate) pumping time is 242 hours. Since construction costs are much lower than electricity costs in Iran, it is clear from Scenarios 1 through 4 that the optimization approach favors the addition of a significant volume of reservoir storage in order to achieve a marginal reduction in pumping time and a reduction in electricity cost. Table 3-2 also indicates that discount rate has only a small impact on the mass of GHG emissions in the KamalSaleh system where the difference between GHG mass between Scenario 1 (status quo) and Scenarios 4 is
2.8%. This decrease in GHG mass is attributed to an increase in reservoir volume which tends to decrease pumping time slightly.

3.6.2 Impact of a Carbon Tax on Optimal Design, Costs, Electricity Use, and GHG Emissions

The carbon tax was increased from $0 / tonne CO2-e (Scenario 1) to $10 - $180 / tonne CO2-e in Scenarios 5 through 10 to examine its impact on storage volume, pumping time, and GHG emissions in the KamalSaleh system. In these scenarios, discount rate for electricity was held fixed at the ‘status quo’ level of 8% and social discount rates for GHG emissions were fixed at 0% (suggested by Hasselmann et al. (1997) and Fearnside (2002)) and 8%. Table 3-2 indicates that when social discount rate is set to 0% and 8% for GHG emissions, increasing the carbon tax from $10 to $180 / tonne CO2-e increases reservoir volume by approximately 2 - 36% and decreases the GHG mass by 3.3-3.6% (relative to the status quo scenario). The larger reservoir volume increases average water levels and decreases the dynamic pumping head required by the system and the associated GHG mass generated in electricity production.

3.6.3 Combined Impact of a Carbon Tax and Discount Rates on the Optimal Design, Costs, Electricity Use, and GHG Emissions

The effect of lowering discount rate and increasing the carbon tax simultaneously on the optimization of the KamalSaleh system was also examined. The carbon tax was increased from $10 to $50 / tonne CO2-e while discount rates were decreased from 4% to 0% in Scenarios 11 through 16. Scenario 17 is the most aggressive scenario where discount rate is set to 0% and the carbon tax is set to $180 / tonne CO2-e. Table 3-2 indicates that increasing the carbon tax from $10 to $50 / tonne CO2-e and decreasing discount rate from 4% to 0% increased reservoir volume by 14% and produced no significant reduction in pumping time. Table 3-2 indicates that even the
scenarios with low discount rates and a high carbon tax only reduce the GHG mass by a small amount. For example, Scenario 17, the most ambitious scenario, reduces the GHG mass by only 3.7% relative to the status quo scenario. Further, Scenario 13, the least ambitious mitigation scenario, reduces the GHG mass by only 2.2% relative to the status quo scenario. Owing to the stochasticity of the EGA search process, it is difficult to ascertain the source and significance of these slight differences in GHG mass.

3.7 Multi-Objective Optimization Results

Four discounting and carbon tax scenarios were selected to optimize the KamalSaleh transmission system with the multi-objective NSGA-II. The Pareto-optimal solutions generated in these four scenarios are indicated in Figure 3.4. The x-axis in this figure indicates the capital cost of constructing reservoir storage while the y-axis indicates the net present value of operational cost (electricity and taxes levied on greenhouse gas emissions) in the KamalSaleh system. For each scenario, the solutions with the minimum capital cost (Solution 1 in Table 3-3), minimum operational cost (Solution 3 in Table 3-3), and minimum total cost (Solution 2 in Table 3-3) are indicated with the rest of the non-dominated solutions in Figure 3.4. The details of each solution are indicated in Table 3-3.

The results in Figure 3.4a and b indicate that when electricity and greenhouse gases are discounted at 8% and 0% respectively, increasing the carbon tax from $0 / tonne CO2-e (Figure 3.4a, Scenario 1 in Table 3-3) to $180 / tonne CO2-e (Figure 3.4b, Scenario 2 in Table 3-3) increases the steepness of the Pareto front. To a lesser extent, decreasing the electricity discount rate from 8% (Figure 3.4a, Scenario 1) to 0% (Figure 3.4c, Scenario 3) also increases the steepness of the Pareto front and reduces the range of capital costs. Increasing both the carbon tax from $0 tonne CO2-e (Figure 3.4a, Scenario 1) to $180 tonne CO2-e (Figure 3.4d, Scenario 4)
and decreasing electricity discount rate from 8% to 0% further increases the steepness of the Pareto front.

Increasing the carbon tax and decreasing discount rate have the effect of magnifying the weighting on recurring operational costs such that any incremental change in reservoir storage will result in significant increases (or decreases) in operational costs in the system. From a decision-making vantage point, this means that under conditions of a high carbon tax and low discount rates, only modest investments in reservoir storage will produce significant reductions in operational cost in the KamalSaleh system.

The data in Table 3-3 indicate that both discount rate and carbon tax have only a small effect on the GHG mass generated in the KamalSaleh system. When the discount rate of electricity is lowered from 8% to 0% and carbon tax is held at $0 / tonnes CO2-e (discount rate of GHG is held at 0%) across Scenarios 1 and 3, the change in GHG mass is 1.6%. This is owing to the low electricity discount rate that places a large weight on future operational costs and that encourages the search process to select solutions with higher average water levels to reduce pump operation times. When the carbon tax is increased from $0 to $180 / tonnes CO2-e (both discount rate of electricity and GHG are held at 0%) across Scenarios 3 and 4, the GHG mass is reduced by 4.1% due to an increase in the pump operation time. Further, when both the discount rate of electricity is lowered from 8% to 0% and the carbon tax is increased from $0 to $180 / tonnes CO2-e (discount rate of GHG is held at 0%) across Scenarios 1 and 4, the GHG mass is reduced by 6.0%. This suggests that a low discount rate in combination with a high carbon tax can produce moderate reductions in GHG mass in the KamalSaleh system.
Figure 3.4 Non-dominated solutions generated for discounting and carbon tax: a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, where electricity discount rate = DR(elec), greenhouse gas cost discount rate = DR(GHG), carbon tax = CT.
Table 3-3 GHG mass, GHG cost, electricity cost, reservoir construction cost, and total cost for a range of discounting and carbon tax scenarios in the multi-objective optimization of the KamalSaleh system.

<table>
<thead>
<tr>
<th>Scenario No.</th>
<th>Disc. Rate Elec. (%)</th>
<th>Disc. Rate GHG ($)/tonne</th>
<th>GHG Tax (0-25 yr)</th>
<th>GHG Mass (kg/day)(1)</th>
<th>Total GHG Mass (tonne)</th>
<th>GHG Cost ($M)(2)</th>
<th>Elec. Cost ($M)</th>
<th>Reservoirs Cost ($M)</th>
<th>Reservoir Volume (m³)</th>
<th>Pumping Time (hours)</th>
<th>Total Operational Cost ($M)</th>
<th>Total Cost ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8%</td>
<td>0%</td>
<td>0</td>
<td>1</td>
<td>68,443</td>
<td>82,198</td>
<td>1,374,597</td>
<td>0.0</td>
<td>110.4</td>
<td>5.4</td>
<td>54100</td>
<td>248.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>68,320</td>
<td>81,064</td>
<td>1,363,128</td>
<td>0.0</td>
<td>110.2</td>
<td>5.6</td>
<td>55600</td>
<td>243.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>67,707</td>
<td>81,463</td>
<td>1,361,172</td>
<td>0.0</td>
<td>109.4</td>
<td>8.5</td>
<td>84800</td>
<td>248.0</td>
</tr>
<tr>
<td>2</td>
<td>8%</td>
<td>0%</td>
<td>180</td>
<td>1</td>
<td>66,397</td>
<td>78,268</td>
<td>1,320,069</td>
<td>789.4</td>
<td>109.9</td>
<td>3.8</td>
<td>38400</td>
<td>247.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>65,572</td>
<td>77,507</td>
<td>1,305,600</td>
<td>783.0</td>
<td>109.0</td>
<td>5.0</td>
<td>50400</td>
<td>244.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>65,572</td>
<td>77,507</td>
<td>1,305,600</td>
<td>783.0</td>
<td>109.0</td>
<td>5.0</td>
<td>50400</td>
<td>244.1</td>
</tr>
<tr>
<td>3</td>
<td>0%</td>
<td>0%</td>
<td>0</td>
<td>1</td>
<td>67,550</td>
<td>79,941</td>
<td>1,345,850</td>
<td>0.0</td>
<td>469.5</td>
<td>4.9</td>
<td>48600</td>
<td>245.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>67,545</td>
<td>79,497</td>
<td>1,341,760</td>
<td>0.0</td>
<td>467.7</td>
<td>5.3</td>
<td>52600</td>
<td>244.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>66,303</td>
<td>79,066</td>
<td>1,326,491</td>
<td>0.0</td>
<td>467.2</td>
<td>6.4</td>
<td>64400</td>
<td>245.7</td>
</tr>
<tr>
<td>4</td>
<td>8%</td>
<td>0%</td>
<td>180</td>
<td>1</td>
<td>65,650</td>
<td>79,062</td>
<td>1,320,499</td>
<td>800.2</td>
<td>474.2</td>
<td>4.4</td>
<td>43700</td>
<td>248.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>64,810</td>
<td>76,212</td>
<td>1,286,824</td>
<td>786.8</td>
<td>466.3</td>
<td>5.3</td>
<td>53100</td>
<td>247.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>64,810</td>
<td>76,212</td>
<td>1,286,824</td>
<td>786.8</td>
<td>466.3</td>
<td>5.3</td>
<td>53100</td>
<td>243.3</td>
</tr>
<tr>
<td>5</td>
<td>8%</td>
<td>8%</td>
<td>180</td>
<td>1</td>
<td>67,101</td>
<td>80,748</td>
<td>1,349,122</td>
<td>187.0</td>
<td>110.8</td>
<td>5.8</td>
<td>57800</td>
<td>250.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>65,674</td>
<td>79,496</td>
<td>1,324,671</td>
<td>185.3</td>
<td>109.8</td>
<td>6.7</td>
<td>66700</td>
<td>247.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>65,772</td>
<td>79,137</td>
<td>1,322,293</td>
<td>185.2</td>
<td>109.8</td>
<td>7.3</td>
<td>73300</td>
<td>246.7</td>
</tr>
</tbody>
</table>

(1) The change in GHG mass linked to the dynamic pumping head only was reported in this table.

(2) All costs are in million dollars.
3.8 Discussions and Interpretation of Results

To the authors’ knowledge, there are no known policies on discounting and carbon tax to reduce greenhouse gas emissions in the water industry in Iran. Despite this, the government of Iran is a signatory to the Kyoto climate change agreement and it is vigorously trying to reduce their emissions. The KamalSaleh system is representative of water transmission projects in Iran. Most water transmission systems in the country have been designed to lift water over usually mountainous terrain across an average transfer distance of 62 km (Roshani 2012b). The results of the current study have made clear that decreasing discount rate and increasing the carbon tax have only a small effect (less than 8%) in reducing energy use and greenhouse gas emissions in the KamalSaleh system. This is owing to the fact that the static lift requirement accounts for 70% of the total dynamic head and that this lift is largely unaffected by a change in pumping patterns and the addition of more reservoir storage in response to a lower discount rate and higher carbon tax. While firm recommendations cannot be made based on this single case study, the results from the KamalSaleh indicate that discount rate and carbon tax have little effect on inducing changes in pumping patterns and reservoir storage that can significantly reduce energy use and greenhouse gas emissions in high-lift systems. Further studies of high-lift systems are required to make such a firm recommendation.

In the KamalSaleh system, the reservoir construction cost accounted for 1-5% of the total cost, while electricity and GHG costs accounted for more than 95% of total cost. This is owing to the fact that labor cost in Iran are currently very low ($6/day minimum wage, IML 2012). In the single-objective optimization study, the low construction cost encouraged the addition of significant reservoir storage to achieve slight decreases in electricity and GHG costs. In future
studies, the large difference between labor cost and electricity cost will have to be revisited in order to achieve a better balance between these two factors in the optimization.

The results of this study have begun to shed light on the effectiveness of discount rate and carbon tax in a high-lift water transmission system. More research is needed to examine the effectiveness of discount rate and carbon tax in reducing energy use and greenhouse gas emissions in low-lift transmission system with different topographies, a range of water demand levels and diurnal patterns, a range of pipeline diameters, and a range of reservoir configurations. With this additional research, it will be possible to make recommendations on the effectiveness of discount rate and carbon tax in reducing energy use and greenhouse gas emissions in systems with certain combination of lift, demand, and other characteristics.

3.9 Summary and Conclusions

The research examined the impact of a carbon tax and discount rates on the optimization of the KamalSaleh water transmission system in KamalSaleh, Iran. Single-objective and multi-objective optimization approaches were applied to the design of the KamalSaleh water transmission pipeline to examine the effect of decreasing discount rate and increasing the carbon tax levied on electricity to reduce energy use and greenhouse gases. The single-objective results indicated that increasing the carbon tax and lowering discount rate had a noticeable impact on capital costs, reservoir storage in the system and in reducing greenhouse gas emissions in the KamalSaleh system. Under these conditions, the installation of additional storage capacity, along with the use of a low discount rate and a high carbon tax, can produce a moderate reduction in energy use and GHG emissions in the KamalSaleh system. Multi-objective results indicated that decreasing the discount rate and increasing the carbon tax increased the steepness of the Pareto front which suggested that modest investments in reservoir storage produced significant reductions in
electricity and GHG costs in the KamalSaleh system. More research is needed to examine the effectiveness of discount rate and carbon tax in reducing energy use and greenhouse gas emissions in low-lift and high-lift transmission systems with different topographies, a range of water demand levels and diurnal patterns, a range of pipeline diameters, and a range of reservoir configurations.

3.10 Acknowledgements
The authors wish to thank the Natural Science and Engineering Research Council (NSERC) and Queen’s University for their financial support of this research. Also authors thank Lar Consulting Engineers for providing the required data.

3.11 References


International Energy Agency (IEA) (2012) Monthly Electricity Statistic, 


Lar consulting engineers (2005a) KamalSaleh Transmission Pipeline Engineering Design Report, Tehran, Iran.


Chapter 4
 Evaluating the Impact of Climate Change Mitigation Strategies on the Optimal Design and Expansion of the Fairfield, Ontario Water Network: A Canadian Case Study

4.1 Abstract
The objective of this research is to assess the impact of proposed Canadian climate change mitigation policies (discounting and carbon pricing) on cost, energy use and greenhouse gas (GHG) emissions in the single-objective design/expansion optimization of the Fairfield water distribution system in Amherstview, Ontario, Canada. The single-objective optimization problem is solved with the Elitist Genetic Algorithm (EGA). The optimization approach is used in a parametric analysis to examine the impact of discounting and carbon pricing on GHG reductions for cement-mortar ductile iron and polyvinyl chloride pipe materials. Results indicate that the discount rate and carbon prices investigated had no significant influence on energy use and GHG mass in the Fairfield system and did not meet the emission-reduction targets set by the Canadian Government. This result was attributed to a number of factors including, adequate installed hydraulic capacity in the Fairfield system, the use of a time-declining GHG emission intensity factor, and the scope of the expansion problem.

Keywords: water distribution systems, greenhouse gas emissions, environmental sustainability, environmental impact, optimization, material selection.

4.2 Introduction
The water industry is energy and carbon-intensive. In the U.S., one estimate indicates that the energy used to pump, treat, and heat water is equal to 13% of all U.S. electricity generation
(Griffiths-Sattenspiel and Wilson 2009). It is estimated that the 60,000 water systems and 15,000 wastewater systems in the US use approximately 75 billion kWh/yr of electricity which amounts to 3% of electricity generated in the US annually (Electric Power Research Institute 1994). Clarke et al. (2009) estimated that water provision and water heating account for 6% of all greenhouse gases (GHG) emitted in the UK. In Canada water provision services are carbon-intensive primarily because electricity is generated with fossil fuels in many parts of the country (Cuddihy et al. 2005). The raw material extraction, material production, manufacturing, transport and installation activities associated with pipes and other components (e.g., water treatment plants, pipes, pumps and tanks) are also linked with the use of electricity and liquid fuels (such as diesel and gasoline) and generation of GHGs. With aging infrastructure, there is an urgent need to retrofit and upgrade water networks to maintain a high level of water service to customers in Canada. The consideration of GHG emissions in water network design and expansion will be increasingly important for water utilities as policy makers in Canada develop climate change mitigation policies centered around low discount rates and carbon pricing strategies to meet the Canadian Government’s 2020 (20% below 2006 levels) and 2050 (65% below 2006 levels) emission reduction targets.

The objective of this research is to assess the impact of proposed GHG mitigating strategies (low discount rates and carbon pricing) in Canada on cost, energy use and greenhouse gas emissions in the design/expansion optimization of the Fairfield water distribution system in Amherstview, Ontario, Canada. The Fairfield case study considers a discount rate proposed by the Treasury Board of Canada Secretariat and a discount rate proposed in the Stern Review (Stern et al. 2006) as well as carbon price trajectories developed by the Canadian National Round Table on the Environment and the Economy (NRTEE). Polyvinyl chloride (PVC) and cement-mortar lined ductile iron (DCLI) pipe materials are considered in the optimization of the Fairfield system.
The chapter is organized as follows. First, previous research in planning, design, and optimization of water networks for sustainability is reviewed. Second, proposed Canadian carbon pricing policy and discounting practices are discussed. Third, the single-objective optimization approach is presented and applied to the Fairfield system and the results of the analysis are discussed.

4.3 Research in Planning, Design, and Optimization of Water Distribution Networks for Environmental Sustainability

A number of researchers have used systems-level tools such as life-cycle analysis (LCA) to evaluate water system design and expansion planning in light of both environmental and socio-economic considerations. Dennison et al. (1999) utilized LCA to identify stages where environmental impacts could be reduced in the life-cycle of ductile iron and medium density polyethylene pipe materials. Filion et al. (2004) selected energy as a key environmental measure and performed a life-cycle energy analysis (LCEA) to quantify energy expenditures in the fabrication, use, and end-of-life stages of a water distribution network. Lundie et al. (2004, 2005) and Stokes and Horvath (2006) applied LCA to examine the environmental impacts of alternative strategic planning scenarios. Ghimire and Barkdoll (2007) discussed the use of Eco-Efficiency Analysis—a coupling of life-cycle cost analysis (LCCA) with LCA—to generate an environmental impact score and guide water network planning and development decisions.

Incorporating sustainability criteria in single- and multi-objective optimization of water distribution network design and expansion has been proposed by a number of researchers. Dandy et al. (2006) developed a genetic algorithm (GA) optimization model with the sustainability objective of minimizing pipe material usage. Dandy et al. (2008) were among the first to consider sustainability objectives in conjunction with least-cost optimization in a multi-objective approach.
In their study, the authors developed a multi-objective GA to minimize pipe embodied energy and total present value cost. Herstein et al. (2009, 2010) developed an environmental impact index based on economic input-output life-cycle assessment that was integrated into a multi-objective GA optimization program and applied to the benchmark ‘Anytown’ test network.

More recently, Wu et al. (2009) investigated whether the introduction of carbon pricing under an emissions trading scheme will make the use of a multi-objective optimization approach for the design of new water distribution systems obsolete. In this study a number of constant market-based carbon costs and social costs of carbon (SCC) were investigated. The authors assumed a constant discount rate of 8% for the present value analysis of cost (capital and operating), while GHG emission costs (both market-based and SCC) were discounted using a zero discount rate. Wu et al. (2008, 2010) utilized a multi-objective GA to explore the impacts of minimizing the mass of GHG emissions (resulting from the fabrication and operation of water distribution networks) and total present value cost on the design of a new water distribution network. A sensitivity analysis was conducted using discount rates of 0%, 1.4%, 2%, 6%, 8% and a declining discount rate in present value analysis for computing both system pumping cost and the mass of greenhouse gas emissions. Capital GHG emissions were calculated using pipe embodied energy values published in Ambrose et al. (2002). Data on these factors are not yet available in Canada.

The present research builds upon the work of Wu et al. (2009, 2010) to investigate the influence of proposed Canadian carbon mitigating policies on the single-objective water distribution design/expansion optimization problem. The present research is the first ever to examine a GHG-based optimization of a real-life, all-pipes network with a realistic level of complexity (345 pipe segments and 346 nodes, 2 pumping stations with pump/tank controls, and three fluctuating head tanks). The present study provides insights into the effectiveness and impact of GHG mitigation (e.g., discounting and carbon tax) in a real network that is not otherwise accessible through case
studies of simplistic systems. The research is also the first ever to consider a real proposed policy on time-varying carbon pricing as well as time-varying GHG emission factors that reflects an actual forecast in electricity fuel mixtures in Canada.

4.3.1 NRTEE Carbon Pricing

In 2009, the National Round Table on the Environment and the Economy proposed a carbon pricing policy framework for Canada to achieve the Canadian Government’s 2020 and 2050 emission reduction targets (NRTEE 2009). At the core of the proposed framework is an economy-wide cap-and-trade system that sets the annual level of emissions reductions by issuing emissions permits (NRTEE 2009). With permit auctioning, the Canadian water industry will incur an additional cost on fossil fuel-derived electricity (such as coal and natural gas) used to operate treatment and pumping facilities in networks.

NRTEE (2009) modeling suggests GHG market-based permit prices in the range of the “Fast and Deep” cost trajectory (Table 4-1) are required to change the relative cost of fuel and technologies so that low-carbon technology is deployed and consumer behaviour changes at a level sufficient to achieve the government’s medium- and long-term emission reduction targets. It is acknowledged by NRTEE (2009) that lower permit prices could be expected if Canada were to engage in international carbon emissions trading. Thus in this study two NRTEE carbon price trajectories will be investigated: “Fast and Deep” and “Slow and Shallow” (Table 4-1). It should be noted that emission prices predicted beyond 2025 are speculative due to market uncertainty (NRTEE 2007).

4.3.2 Social Discount Rates Suggested by the Treasury Board of Canada

The social discount rate is defined as the minimum real rate of return that a public investment must earn if it is to be worthwhile undertaking (Boardman et al. 2008). The social discount rate is
intended to reflect the real rate of return foregone in the private sector when resources are shifted into the public sector (Burgess 1981). Discounting has significant implications on the economic analysis of public projects with long-term GHG implications as high discount rates minimize the influence of future climate-related environmental impacts and costs on the net present value of a project (Nordhaus 1991, Cline 1992).

Table 4-1 NRTEE carbon price trajectories: “No tax”, “Slow and shallow” and “Fast and Deep”

<table>
<thead>
<tr>
<th>Year</th>
<th>“No tax”</th>
<th>“Slow and shallow”</th>
<th>“Fast and deep”</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>2020</td>
<td>0</td>
<td>30</td>
<td>75</td>
</tr>
<tr>
<td>2025</td>
<td>0</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>2030</td>
<td>0</td>
<td>75</td>
<td>225</td>
</tr>
<tr>
<td>2035</td>
<td>0</td>
<td>100</td>
<td>270</td>
</tr>
<tr>
<td>2040+</td>
<td>0</td>
<td>200</td>
<td>270</td>
</tr>
</tbody>
</table>

Selecting an appropriate discount rate has been a policy issue in Canada for many years (Jenkins and Kuo 2007). The Treasury Board of Canada has recently recommended a discount rate of approximately 8% (TBS 2007). In the United Kingdom, Stern et al. (2006) advocate the use of a constant near-zero discount rate of 1.4% to reduce the risk of future climate damages. This paper will explore the impact of the Treasury Board of Canada discount rate of 8% and the Stern Review discount rate of 1.4%. The use of a zero discount rate for GHG emission costs has also been suggested by authors Hasselmann et al. (1997) and Fearnside (2002) to calculate the net present value of climate change costs. However, as this discounting method is used in conjunction with GHG costs expressed as social costs of carbon, it would not be appropriate to apply this discounting method to Canadian market-based GHG costs since they would experienced by water
utilities as an additional surcharge on their electricity bill. For this reason, in this study, capital costs, operating costs and GHG costs are discounted using the same constant discount rate.

4.4 Problem Formulation

The optimization approach developed in this paper aims to identify network expansion solutions that minimize the cost of water main capital improvements, the cost of electricity used to pump water, and the cost associated with a carbon price levied on electricity used for pumping water in the Fairfield system. The decision variables of the optimization problem include the diameter of new PVC and DCLI pipes, the diameter of duplicate PVC and DCLI pipes, and the cleaning and lining of existing pipes in the network. Note that although the cleaning is a separate activity than the lining but since a pipe is often cleaned before lining therefore the cost accounts for both of these activities together. It was determined that the Fairfield network has adequate tank and pump capacity, and so the setting and sizing of new elevated tanks and pump stations were not included as decision variables in the optimization problem.

Minimize: \( \text{TotalCost} = C_{\text{Capital}} + C_{\text{Operating}} + C_{\text{GHG}} \)  

where \( C_{\text{Capital}} \) = present value cost of new and duplicate pipes and cleaning and lining of existing pipes ($); \( C_{\text{Operating}} \) = present value cost of electricity for pumping ($); and \( C_{\text{GHG}} \) = present value cost of GHG emissions generated in electricity production for pumping ($). Capital cost \( (C_{\text{Capital}}) \) is calculated as

\[
C_{\text{Capital}} = \sum_{i=1}^{PP} C_p(d_i, L_i) + \sum_{j=1}^{M} C_{CL}(d_j, L_j)
\]

where \( PP \) = number of new and duplicate pipes in the system; \( C_p(d_i, L_i) \) = cost of new pipe \( i \) with diameter \( d_i \) and length \( L_i \); \( M \) = number of existing pipes that are cleaned and lined; and
$C_{CL}(d_j, L_j) =$ cost of cleaning and lining pipe $j$ with diameter $d_j$ and length $L_j$. Note that all pipe interventions (e.g., installation of new pipes in new developments, duplication of existing pipes, and cleaning and lining of existing pipes) occur at the beginning of the design horizon (time $t = 0$) of the system.

Operating costs ($C_{Operating}$) and GHG costs ($C_{GHG}$) occur annually throughout the design life of the project and are calculated with net present value (NPV) analysis. Operating costs are calculated as

$$C_{Operating} = \sum_{p=1}^{PMP} \sum_{t=1}^{T} PV\left(PE_{p,t} \cdot EC\right)$$

(3)

where $PMP =$ number of existing pumps in the network; $T =$ number of years in the design life of the project; $PE_{p,t} =$ annual electricity consumption of pump $p$ in year $t$ (kWh); and $EC =$ price of electricity ($/kWh$). The mass of GHGs emitted over the design life of a water network can be calculated as follows

$$GHG_e = \sum_{p=1}^{PMP} \sum_{t=1}^{T} PV\left(PE_{p,t} \cdot EIF_t\right)$$

(4)

where $GHG_e =$ total GHG mass generated in network operation (tonne CO2-e); and $EIF_t =$ GHG emission intensity factor for year $t$ (tonne CO2-e/kWh). GHG costs are calculated using (5)

$$C_{GHG} = \sum_{p=1}^{PMP} \sum_{t=1}^{T} PV\left(PE_{p,t} \cdot EIF_t \cdot CP_t\right)$$

(5)

where $CP_t =$ the cost of carbon in year $t$ ($/tonne CO2-e$).

Subject to:

(a) Conservation of mass at nodes and energy conservation around loops:
\[ \sum Q_{\text{in}} - \sum Q_{\text{out}} = Q_e \]  \hspace{1cm} (6)

\[ \sum_{\text{loop}} h_f - \sum_{\text{loop}} E_p = 0 \]  \hspace{1cm} (7)

(b) Minimum pressure requirements:

\[ h_i \geq h_{i,\text{min}} \text{ for } i = 1,2,\ldots,N \]  \hspace{1cm} (8)

(c) Maximum velocity constraint:

\[ V_i \leq V_{i,\text{max}} \text{ for } i = 1,2,\ldots,N_p \]  \hspace{1cm} (9)

(d) Commercially-available pipe diameter constraints:

\[ D_i \in D \text{ for } i = 1,2,\ldots,M \]  \hspace{1cm} (10)

where \( Q_{\text{in}} \) = the flow of water into the junction (l/s); \( Q_{\text{out}} \) = the flow of water out of the junction (l/s); and \( Q_e \) = the demand at the junction node (l/s); \( h_f \) = headloss in each pipe (m); \( E_p \) = pumping head (m); \( h_i \) = pressure head at node i (m); \( h_{i,\text{min}} \) = minimum pressure head required at node i (m); \( N \) = number of network nodes; \( V_i \) = fluid velocity in pipe i (m/s); \( V_{i,\text{max}} \) = maximum allowable fluid velocity in pipe i (m/s); \( N_p \) = number of network pipes; \( D_i \) = diameter of pipe i (mm); D = set of discrete commercially-available pipe diameters; and \( M \) = number of pipes.

Design solutions are generated using the Elitist Genetic Algorithm (EGA) (Bhandari et al. 1996; Majumdar and Bhunia 2007) and the EPANET2 hydraulic solver (Rossman 2000) is used to evaluate constraints (6)-(10) and the hydraulic performance of the network (maximum velocity and minimum pressure limits) under average day and peak demands. Unlike a standard GA, the EGA copies the best chromosomes over to the next generation (elitism) and generates the remaining solutions by crossover and mutation operations. Retaining the fittest chromosomes and copying them to the next generation increases the performance of the GA search process (Bhandari et al. 1996; Majumdar and Bhunia 2007). In the EGA, design solutions that violate the
minimum pressure constraint in (8) and the maximum velocity constraint in (9) under maximum hour and/or maximum day + fire demand are assigned a ‘penalty error’ that is added to the objective function value in (1). The ‘penalty error’ inflates the cost in the objective function and thus decreases the likelihood that these solutions are carried forth in the next generation of the GA search process.

4.5 Case Study: Optimization of the Fairfield Water Distribution Network

The Fairfield system provides drinking water to the communities of Amherstview and Odessa which have a combined population of approximately 15,000 people. The all-pipes model of the Fairfield system is indicated in Figure 4.1. Storage capacity includes a 0.9 megalitre (ML) in-ground reservoir located at the Fairfield Water Treatment Plant in Amherstview (R1), a 1.1 ML standpipe in Amherstview (T1), a 4.2 ML ground storage tank in Amherstview (T3) and a 0.9 ML elevated standpipe in Odessa (T2). The design horizon for the case study is 50 years spanning 2009 – 2058.

![Figure 4.1 Layout of Fairfield water distribution network.](image-url)
Three identical high-lift pumps (‘High-Lift Pumps’ in Figure 4.1) in parallel (two online and one standby) provide water to the Town of Amherstview and the Town of Odessa. Also, three identical pumps in parallel (two online and one standby) in the County Road 6 Booster Station transfer water from the Fairfield system to Odessa. The rated head, rated flow, speed, rated efficiency, and tank controls for these pumps are indicated in Table 4-2.

Table 4-2 Rated head, rated flow, speed, rated efficiency, and tank controls for high-lift and booster pumps in the Fairfield network.

<table>
<thead>
<tr>
<th>Pump ID</th>
<th>Rated head (m)</th>
<th>Rated flow (liters/s)</th>
<th>Speed (RPM)</th>
<th>Rated efficiency</th>
<th>Pump status</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-lift 1</td>
<td>62.2</td>
<td>57.9</td>
<td>1,770</td>
<td>75</td>
<td>On: Amherstview tank level &lt; 8.8 m; off: Amherstview tank level &gt; 9.8 m</td>
</tr>
<tr>
<td>High-lift 2</td>
<td>62.2</td>
<td>57.9</td>
<td>1,770</td>
<td>75</td>
<td>On: Amherstview tank level &lt; 8.4 m; off: Amherstview tank level &gt; 9.5 m</td>
</tr>
<tr>
<td>High-lift 3</td>
<td>62.2</td>
<td>57.9</td>
<td>1,770</td>
<td>75</td>
<td>On: Amherstview tank level &lt; 8.0 m; off: Amherstview tank level &gt; 9.2 m</td>
</tr>
<tr>
<td>Booster 1</td>
<td>88.3</td>
<td>27.8</td>
<td>3,600</td>
<td>75</td>
<td>On: Odessa tank level &lt; 9.49 m; off: Odessa tank level &gt; 10.5 m</td>
</tr>
<tr>
<td>Booster 2</td>
<td>88.3</td>
<td>27.8</td>
<td>3,600</td>
<td>75</td>
<td>On: Odessa tank level &lt; 9.49 m; off: Odessa tank level &gt; 10.5 m</td>
</tr>
<tr>
<td>Booster 3</td>
<td>88.3</td>
<td>27.8</td>
<td>3,600</td>
<td>75</td>
<td>On: Odessa tank level &lt; 6.0 m; off: Odessa tank level &gt; 10.5 m</td>
</tr>
</tbody>
</table>

Existing pipe materials in the Fairfield system include cast iron (CI), cement-lined ductile iron (DCLI), concrete (C), steel (S) and polyvinyl chloride (PVC). Since at the start of the 1990s all water mains in Odessa were replaced with new PVC pipe, the addition of new pipes will be limited to the Fairfield system only. The all-pipes water network in Figure 4.1 consists of approximately 41 kilometers of pipe which is represented in EPANET2 with roughly 345 pipe segments and 346 nodes. For computational efficiency, 44 existing pipe segments shorter than 25 m were excluded from the analysis; thus 301 pipe segments are included in the network expansion problem. The diameter, length, and age of existing water mains in the water system (excluding Odessa) are presented in Table 4-3. The Hazen-Williams ‘C’ factors for existing water mains in the Fairfield system were determined by ‘C’ factor flow tests conducted by CH2M Hill (2007). Flow tests produced average ‘C’ values of 55 (DCLI), 100 (S), 120 (C), 130 (DI) and 150 (PVC). Due to a lack of data on existing water mains in the Fairfield system, pipe ageing was not considered in this study.
Table 4-3 Diameter, length, and age of existing water mains in the Fairfield system (excluding Odessa) (CH2M Hill 2007).

| Pipe material | Pipe diameter (mm) | Length (m) | Percentage of total length | Median pipe age |
|---------------|--------------------|------------|---------------------------|----------------|---|
| Concrete      | 400                | 1,342      | 3.2                       | 1993           |   |
|               |                    | Total: 1,342| Total: 3.2                |                |   |
| Cast Iron     | 50                 | 141        | 0.3                       | 1967           |   |
|               | 100                | 257        | 0.6                       | 1962           |   |
|               | 150                | 4,755      | 11.5                      | 1967           |   |
|               | 200                | 2,055      | 5.0                       | 1957           |   |
|               | 250                | 1,864      | 4.5                       | 1967           |   |
| Cast Iron     | 400                | 1,888      | 4.6                       | 1969           |   |
|               |                    | Total: 10,959| Total: 26.4              |                |   |
| Cement-mortar| 50                 | 76         | 0.2                       | 1989           |   |
| lined ductile| 100                | 898        | 2.2                       | 1999           |   |
| iron          | 150                | 5,757      | 13.9                      | 1974           |   |
|               | 200                | 162        | 0.4                       | 2000           |   |
|               | 250                | 29         | 0.1                       | 1974           |   |
|               | 300                | 4,275      | 10.3                      | 2003           |   |
|               | 400                | 2,192      | 5.3                       | 1975           |   |
|               |                    | Total: 13,388| Total: 32.3              |                |   |
| PVC           | 150                | 2,210      | 5.3                       | 2000           |   |
|               | 200                | 4,902      | 12.0                      | 2002           |   |
|               | 250                | 2,716      | 6.5                       | 2002           |   |
|               | 300                | 1,629      | 3.9                       | 1997           |   |
|               | 400                | 4,258      | 10.3                      | 1996           |   |
|               |                    | Total: 15,774| Total: 38.0              |                |   |
| Total length  |                    | 41,464     | 100.0                     |                |   |

4.5.1 Demand Conditions

Water use in the Fairfield system consists of residential (62% of water demand), multi-residential (18%), institutional (8%), industrial (10%) and commercial (2%) (CH2M Hill 2007). The 2009 average day demand for drinking water is 32 L/s. Future water demand to the year 2026 was projected with annual water demand growth rates provided by Loyalist Township, as indicated in Table 4-4 (CH2M Hill 2007). Due to a lack of data on annual water demand growth rates beyond 2026, annual water demand growth rates presented in Table 4-4 were assumed constant to the year 2058 and average day demand in the year 2058 was projected to 153 L/s in Fairfield. CH2M Hill (2007) did not provide any information on future demands or future servicing (pipe layout) beyond the year 2026. However, partner Loyalist Township indicated that future development and demands beyond 2026 would likely expand well north of the geographic location indicated
with grey shaded areas in Figure 4.1. In the analysis, future demand growth in 2026 - 2058 geographically north of the grey shaded areas in Figure 4.1 was lumped and applied to the nodes located in the serviced areas shown in the grey shaded area. This is a modeling approximation that underestimates energy use and greenhouse gas emissions linked to the additional 2026-2058 demand since that additional demand is not conveyed by additional pipes (north of the grey area) at any additional headloss. Water demand in existing developments already at ‘build-out’ (non-shaded areas in Figure 4.1) was held constant at 2009 levels in all scenarios.

Table 4-4 Fairfield annual water demand growth rates and current and future water demands 
(CH2M Hill 2007)

<table>
<thead>
<tr>
<th>Amherstview water use</th>
<th>Annual growth rate (%)</th>
<th>2009 Water demand (liters/s)</th>
<th>2058 water demand (liters/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>3.5</td>
<td>20</td>
<td>107</td>
</tr>
<tr>
<td>Multiresidential</td>
<td>3.5</td>
<td>6</td>
<td>32</td>
</tr>
<tr>
<td>Commercial</td>
<td>2.0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Institutional</td>
<td>2.0</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Industrial</td>
<td>1.0</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>32</td>
<td>153</td>
</tr>
</tbody>
</table>

The 2009 water demand in the Town of Odessa was lumped together in a single value of 6 L/s base demand and assumed fixed over the 50-year design horizon (no growth). The diurnal pattern used in the analysis was applied to the 6 L/s base demand in Odessa. Average daily demand in the water distribution system was modeled as an extended period simulation with the average-day diurnal pattern in Figure 4.2. The diurnal pattern was constructed with SCADA data collected over a two-week period in August 2005 and April 2006 (CH2M Hill 2007).

Maximum hour demand (MHD) and maximum day demand (MDD) plus required fire flow were considered to evaluate the minimum pressure constraint in (8) and the maximum fluid velocity
constraint in (9) in the Fairfield expansion problem. Peaking factors for MHD and MDD were set at 2.0 and 1.5 respectively (CH2M Hill 2007). Fire simulations were carried out on two critical nodes J-514 and J-551 in Fairfield in Figure 4.1. A needed fire flow of 33 L/s was adopted for residential construction at a residual pressure of 137 kPa for the duration of 1 hour in accordance with the Fire Underwriters Survey (FUS) guidelines (FUS 1999). The minimum pressure required in the system during average-day and MHD simulation is 275 kPa (CH2M Hill 2007).

Figure 4.2 Fairfield water distribution system average-day diurnal curve (data from CH2M Hill 2007)

4.5.2 Capital Costs
To quantify the cost of new PVC and DCLI pipes, unit prices for these pipe materials were obtained from Canadian pipe distributors (Table 4-5). For consistency with subdivision development and design practices in Ontario, Canada, minimum pipe diameters for new pipes and duplicate pipes were set to 200 mm and 150 mm respectively. Pipe installation costs (excavation, pipe laying, bedding, backfill and restoration) were excluded from the analysis because these data was not available in the Fairfield study. Including pipe installation costs in the analysis would increase pipe and capital costs in the objective function (1) and perhaps guide the search process
to choose solutions that minimize pipe diameter and pipe cost in (1). This would likely have an impact on the balance between capital costs and electricity and GHG costs in (1) and on the GA search process.

Table 4-5 Unit costs of new commercially-available PVC and DCLI pipe diameters and unit cost of cleaning and cement-mortar lining existing pipes (from Walski 1986).

<table>
<thead>
<tr>
<th>Pipe material</th>
<th>PVC</th>
<th>DCLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter (mm)</td>
<td>Inside diameter (mm)</td>
<td>Unit price ($/m)</td>
</tr>
<tr>
<td>150</td>
<td>160</td>
<td>29.00</td>
</tr>
<tr>
<td>200</td>
<td>210</td>
<td>48.00</td>
</tr>
<tr>
<td>250</td>
<td>258</td>
<td>72.00</td>
</tr>
<tr>
<td>300</td>
<td>307</td>
<td>97.00</td>
</tr>
<tr>
<td>350</td>
<td>356</td>
<td>102.81</td>
</tr>
<tr>
<td>400</td>
<td>404</td>
<td>133.88</td>
</tr>
<tr>
<td>450</td>
<td>453</td>
<td>169.30</td>
</tr>
<tr>
<td>500</td>
<td>502</td>
<td>209.82</td>
</tr>
<tr>
<td>600</td>
<td>600</td>
<td>303.62</td>
</tr>
</tbody>
</table>

The manufacturer-recommended ‘C’ factors for PVC and DCLI are 150 and 140 respectively. In the absence of available data on new PVC and DCLI pipe aging, ‘C’ factors were assumed to remain constant at their manufacturer-specified values over the 50-year design life of the Fairfield system.

Pipe cleaning and cement-mortar lining costs for existing pipes were estimated using costs from Walski (1986) and are presented in Table 4-5. In accordance with the Walski (1986) methodology, cleaning and lining cost estimates were adjusted to 2009 dollars using the Engineering News Report (ENR) Construction Cost Index (ENR 2009). Costs were converted from US dollars to Canadian dollars using the average exchange rate of 1.16 reported by the Bank of Canada (2009) for the last 12 months. Cleaning and lining costs include labour, materials, equipment, and contractor overhead and profit, and exclude excavation, mobilization, temporary service and valve replacement costs (Walski 1986). For existing pipes that are cleaned and cement-mortar lined, ‘C’ factor values have been taken from the research literature. Hudson
(1966) found that cleaned and lined concrete pipes had an average ‘C’ factor of 130, while in Larson and Sollo (1967) the ‘C’ factor of cleaned and lined cast iron pipe was found to have an average value of 110. According to the findings of Hudson (1966), cement-mortar lined pipes were assumed to retain their ‘C’ factor values to the end of the 50-year design life of the Fairfield system (Hudson 1966).

4.5.3 Operational Cost

To calculate energy use over the 50-year time horizon, the authors divided the 50-year time horizon into two periods each lasting 25 years. In the first 25-year period, annual energy use was calculated by entering the 2009 average day demands and the diurnal pattern (Figure 4.2) (CH2M Hill 2007) into a network solver (EPANET2) and computing pumping heads and pumping flow rates over a 24-hour extended period. The pumping heads and flow rates were then entered into the brake horsepower equation which was integrated over the 24-hour diurnal period to calculate daily energy use. Annual energy use was calculated by multiplying daily energy use by 365 days. The energy use over the first 25-year period was calculated by multiplying the annual energy use by 25 years. The same procedure was applied to the second 25-year period with the 2058 average day demand and the diurnal pattern in Figure 4.2. The energy calculation above is computationally efficient and appropriate for the optimization application since only two extended period simulations are required to estimate energy use over the 50-year period. The energy calculation is also an approximation since demand growth is captured with only two sets of demands (2009 and 2058). In reality, because demand is continually growing from year to year, a different set of average day demands should be used to calculate annual energy use and total energy use over the 50-year period. However, this approach is computationally more expensive as 50 separate extended period simulations would have to be performed to calculate the annual energy use from year to year over the entire design horizon. The close relationship
between energy use and GHG emissions means that the above approach is also an approximation of GHG emissions generated in the Fairfield network.

Annual operating cost was calculated using an electricity cost of 6.6 cents per kWh – the Regulated Price Plan (RPP) electricity consumption price set by the Ontario Energy Board (OEB 2008). Due to the lack of data on future electricity prices, the electricity price was assumed constant. Given that energy prices are widely anticipated to increase in the future (by an amount as yet unknown), the assumption of a constant electricity price is deemed ‘conservative’ in that it likely underestimates operating costs and total costs in the Fairfield system optimization.

4.5.4 GHG Emissions

GHG emissions from pumping operations in the Fairfield system were calculated using projections of Canada’s future energy fuel mix produced by the National Energy Board (NEB 2007). The baseline ‘Reference Case’ projection produced by NEB (2007) is the most likely forecast of Canada’s electricity mix to the year 2015 and is summarized as follows: hydroelectric generation will increase its contribution from approximately 60% of Canadian electricity generation in the year 2005 to 65% in 2015; nuclear electricity capacity will increase its contribution from 15% to 17%; natural gas will increase its contribution from 7% to 10%; coal’s contribution will fall from 17% in 2005 to 6% in 2015; wind power is projected to increase its contribution from 0.4% in 2005 to 1.1% by 2015; and contributions from unconventional generation technologies, such as biomass, landfill gas, waste heat, solar and tidal will grow from 0.6% of electricity generation to 0.9%.

The ‘Reference Case’ is extended to the year 2030 by the National Energy Board’s ‘Continuing Trends Scenario’ NEB (2007). The ‘Continuing Trends Scenario’ maintains trends that are apparent at the beginning of the outlook over the entire long-term forecast. In the Natural
Resources Canada report prepared by S & T Consultants Inc. (2008), GHG emission intensity factors (EIFs), reported in g CO2-e per kWh, from the NEB (2007) ‘Reference Case’ and ‘Continuing Trends’ Scenario were extrapolated to the year 2050. In the Fairfield study the 2050 GHG EIF is held constant to the year 2058 (Figure 4.3). Since the Canadian average fuel mix is similar to the fuel mix in the Province of Ontario, the projected Canadian average EIFs reported in Figure 4.3 can be applied to the Eastern Ontario region and the Fairfield system (Environment Canada 2009).

Figure 4.3 Forecasted Canadian greenhouse gas emission intensity factors (data from S & T Consultants Inc. 2008)

4.5.5 GHG Cost

The impact of carbon pricing on the optimization of the Fairfield system was investigated for three realistic Canadian carbon pricing scenarios: “No Tax”, NRTEE “Fast and Deep” and NRTEE “Slow and Shallow” (Table 4-1). The “No Tax” price trajectory represents ‘status quo’ carbon pricing in Canada. The NRTEE “Fast and Deep” trajectory corresponds to a cap-and-
trade policy with domestic trading only and the NRTEE “Slow and Shallow” trajectory corresponds to a cap-and-trade policy that includes international carbon trading.

4.6 Results

The capital cost, operating cost, and GHG cost in the Fairfield expansion are presented in Table 4-6 for a range of discount rates and carbon prices to reflect possible climate change mitigating strategies in Canada over the next 50-years. A total of six climate change mitigating scenarios were investigated in Table 4-6 each for PVC and DCLI pipe materials. The “do nothing” climate change mitigation approach corresponds to Scenarios 1 (PVC) and 7 (DCLI) in Table 4-6, where costs are discounted at a rate of 8% and no carbon pricing is adopted. The strongest climate change mitigating policy is represented by Scenario 6 (PVC) and 12 (DCLI) where the discount rate of 1.4% proposed by Stern et al. (2006) is implemented and the NRTEE “Fast and Deep” price trajectory is adopted.

In Table 4-6, total cost increases with decreasing discount rate and a move to a more ambitious carbon price trajectory for both pipe materials. This is because as the discount rate is decreased, increased weight is given to future operating and GHG emission costs. The impact of discount rate and carbon price trajectory on the contributions of capital cost, operating cost and GHG cost

Figure 4.4 Percent contribution of capital cost, operating cost and GHG cost to total cost for (a) PVC and (b) DCLI pipe materials
to total cost of the Fairfield system is indicated in Figure 4.4. With an 8% discount rate and a “FD” carbon price trajectory, GHG costs contribute to only 7% of the total cost for PVC (Scenario 3) and 5% for DCLI (Scenario 9). When the discount rate is reduced to 1.4% at a “FD” carbon price trajectory, the contribution of GHG cost to the total cost reaches 21% for PVC (Scenario 6) and 19% for DCLI (Scenario 12). Capital costs in Table 4-6 vary within a narrow range of $100,000 for PVC pipes and $54,000 for DCLI which suggests that lowering discount rate and increasing carbon price do not force the search algorithm to choose solutions with larger pipe diameters in order to reduce headloss and reduce energy and GHG costs in the Fairfield network.

Table 4-6 Capital cost, operating cost, GHG cost, and total cost of the Fairfield expansion for PVC and DCLI pipe materials under a range of discounting and carbon pricing scenarios.

<table>
<thead>
<tr>
<th>Design scenario</th>
<th>Discount rate (%)</th>
<th>Pipe material</th>
<th>Carbon price trajectory</th>
<th>PVC pipe material</th>
<th>DCLI pipe material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Capital cost</td>
<td>Capital cost</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>PVC</td>
<td>No tax</td>
<td>$978,297</td>
<td>$1,347,028</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>PVC</td>
<td>Slow and shallow</td>
<td>$966,746</td>
<td>$1,309,115</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>PVC</td>
<td>Fast and deep</td>
<td>$966,879</td>
<td>$1,320,018</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>PVC</td>
<td>No tax</td>
<td>$1,066,526</td>
<td>$1,377,574</td>
</tr>
<tr>
<td>5</td>
<td>1.4</td>
<td>PVC</td>
<td>Slow and shallow</td>
<td>$1,034,025</td>
<td>$1,316,033</td>
</tr>
<tr>
<td>6</td>
<td>1.4</td>
<td>PVC</td>
<td>Fast and deep</td>
<td>$969,990</td>
<td>$1,446,513</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>DCLI</td>
<td>No tax</td>
<td>$1,347,028</td>
<td>$1,347,028</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>DCLI</td>
<td>Slow and shallow</td>
<td>$1,309,115</td>
<td>$1,309,115</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>DCLI</td>
<td>Fast and deep</td>
<td>$1,361,929</td>
<td>$1,361,929</td>
</tr>
<tr>
<td>10</td>
<td>1.4</td>
<td>DCLI</td>
<td>No tax</td>
<td>$1,337,574</td>
<td>$1,337,574</td>
</tr>
<tr>
<td>11</td>
<td>1.4</td>
<td>DCLI</td>
<td>Slow and shallow</td>
<td>$1,316,033</td>
<td>$1,316,033</td>
</tr>
<tr>
<td>12</td>
<td>1.4</td>
<td>DCLI</td>
<td>Fast and deep</td>
<td>$1,362,493</td>
<td>$1,362,493</td>
</tr>
</tbody>
</table>

The impact of lowering the discount rate on pumping energy and total mass of GHG emissions is examined by comparing Scenarios 1 and 4 for PVC and Scenarios 7 and 10 for DCLI (Table 4-7). Across these scenarios, the discount rate is reduced from 8% to 1.4% while the carbon price is fixed at $0 per tonne CO2-e. Table 4-7 indicates that discount rate does not have a significant impact on total pumping energy and total mass of GHG emissions in the Fairfield system. For
PVC pipe, a decrease in discount rate from 8% to 1.4% (Scenario 1 to Scenario 4), reduces energy use by 0.5% and GHG emissions by 0.6%. Similarly, for DCLI, a decrease in discount rate from 8% to 1.4% (Scenario 7 to Scenario 10) reduces energy use by 0.8% and GHG emissions by 0.5%. It is noted that the energy use in the second 25-year period is more than three times higher than the energy use in the first 25-year period for all scenarios in Table 4-7. This increase in energy use is owing to a near fivefold increase in average day demand (from 32 L/s in 2009 to 153 L/s in 2058) over the 50-year horizon.

Table 4-7 Energy use and mass of GHG emissions in the Fairfield expansion for PVC and DCLI pipe materials under a range of discounting and carbon pricing scenarios.

<table>
<thead>
<tr>
<th>Design scenario</th>
<th>Total energy use over first 25 years (kWh)</th>
<th>Total energy use over second 25 years (kWh)</th>
<th>Total energy use over 50 years (kWh)</th>
<th>Total greenhouse gas emissions over first 25 years (ton)</th>
<th>Total greenhouse gas emissions over second 25 years (ton)</th>
<th>Total greenhouse gas emissions over 50 years (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC pipe material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8,717,985</td>
<td>28,338,596</td>
<td>37,056,581</td>
<td>1,494</td>
<td>3,452</td>
<td>4,946</td>
</tr>
<tr>
<td>2</td>
<td>8,717,908</td>
<td>28,338,278</td>
<td>37,056,186</td>
<td>1,494</td>
<td>3,452</td>
<td>4,946</td>
</tr>
<tr>
<td>3</td>
<td>8,717,939</td>
<td>28,338,469</td>
<td>37,056,408</td>
<td>1,494</td>
<td>3,452</td>
<td>4,946</td>
</tr>
<tr>
<td>4</td>
<td>8,557,117</td>
<td>28,321,299</td>
<td>36,878,416</td>
<td>1,467</td>
<td>3,450</td>
<td>4,916</td>
</tr>
<tr>
<td>5</td>
<td>8,672,533</td>
<td>28,338,905</td>
<td>37,011,438</td>
<td>1,486</td>
<td>3,452</td>
<td>4,938</td>
</tr>
<tr>
<td>6</td>
<td>8,717,929</td>
<td>28,278,531</td>
<td>36,906,459</td>
<td>1,494</td>
<td>3,444</td>
<td>4,939</td>
</tr>
<tr>
<td>DCLI pipe material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8,629,793</td>
<td>28,528,429</td>
<td>37,158,233</td>
<td>1,479</td>
<td>3,475</td>
<td>4,954</td>
</tr>
<tr>
<td>8</td>
<td>8,731,877</td>
<td>28,513,279</td>
<td>37,244,956</td>
<td>1,497</td>
<td>3,473</td>
<td>4,970</td>
</tr>
<tr>
<td>9</td>
<td>8,628,709</td>
<td>28,714,972</td>
<td>37,343,682</td>
<td>1,479</td>
<td>3,497</td>
<td>4,976</td>
</tr>
<tr>
<td>10</td>
<td>8,873,735</td>
<td>28,002,631</td>
<td>36,876,366</td>
<td>1,521</td>
<td>3,411</td>
<td>4,932</td>
</tr>
<tr>
<td>11</td>
<td>8,532,281</td>
<td>28,015,581</td>
<td>36,547,861</td>
<td>1,462</td>
<td>3,412</td>
<td>4,875</td>
</tr>
<tr>
<td>12</td>
<td>8,731,719</td>
<td>28,513,426</td>
<td>37,245,145</td>
<td>1,497</td>
<td>3,473</td>
<td>4,970</td>
</tr>
</tbody>
</table>

Table 4-7 suggests that the carbon price trajectory has no significant influence on the magnitude of pumping energy and GHG emissions for both pipe materials. At discount rates of 8% and 1.4%, moving from carbon price trajectory “NT” (No tax) to “FD” (fast and deep) produces a change in GHG emissions that ranges from 0% to +0.7% for PVC and DCLI pipe materials. Increasing carbon price is supposed to encourage energy conservation and lead to a decrease in GHG emissions in a water network. However, the results in Table 4-7 indicate that GHG emissions increase slightly with a move to a more ambitious carbon pricing trajectory. This result
points to the fact that carbon pricing has a negligible impact on GHG emissions in the Fairfield network and the stochasticity of the GA search process is largely responsible for the slight increase in GHG emissions across solutions.

The combined influence of a reduced discount rate and strong carbon price trajectory on pumping energy and GHG emissions is assessed by comparing PVC “status quo” Scenario 1 (discount rate = 8%; carbon trajectory = “NT”) and PVC carbon mitigating Scenario 6 (discount rate = 1.4%; carbon trajectory = “FD”). Moving from Scenario 1 to Scenario 6 reduces pumping energy by 0.2% and GHG emissions by 0.2%. For the DCLI pipe material, moving from the “status quo” Scenario 7 to the carbon mitigating Scenario 12 (1.4% discounting and “FD” carbon pricing) increases pumping energy by 0.2% and GHG emissions by 0.3%. These results suggest that the proposed discounting and NRTEE carbon-mitigation strategies have a limited impact in reducing energy use and GHG emissions in the Fairfield system.

*Table 4-8 Percent of mains duplicated, percent of mains cleaned and lined, percent of mains with no intervention for PVC and DCLI pipe materials under a range of discounting and carbon pricing scenarios.*

<table>
<thead>
<tr>
<th>Design scenario</th>
<th>PVC pipe expansion</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of total main duplicated</td>
<td>6.6</td>
<td>6.8</td>
<td>6.8</td>
<td>8.4</td>
<td>7.6</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>Percentage of total main cleaned and lined</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Percentage of total main cleaned and lined and duplicated</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Percentage of total main without intervention</td>
<td>93.2</td>
<td>93.2</td>
<td>93.2</td>
<td>91.4</td>
<td>92.0</td>
<td>93.2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PVC pipe expansion</th>
<th>DCLI pipe expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design scenario</td>
<td>7</td>
</tr>
<tr>
<td>Percentage of total main duplicated</td>
<td>6.1</td>
</tr>
<tr>
<td>Percentage of total main cleaned and lined</td>
<td>0.3</td>
</tr>
<tr>
<td>Percentage of total main cleaned and lined and duplicated</td>
<td>1.0</td>
</tr>
<tr>
<td>Percentage of total main without intervention</td>
<td>92.0</td>
</tr>
</tbody>
</table>

Note: CL = cleaned and lined.

The extent of pipe duplication and cleaning and lining in design Scenarios 1 through 12 are presented in Table 4-8. The majority of duplicate pipes were installed alongside large
transmission mains (300 mm diameter and greater) rather than next to local distribution mains. The results of Table 4-8 indicate that little pipe duplication and pipe cleaning and lining are needed in the system to meet present and future demands. This suggests that there is adequate hydraulic capacity to meet current and future demands.

4.7 Discussion

It was hypothesized that decreasing discount rate and increasing carbon pricing would guide the optimization search to select solutions with extensive pipe duplication and more pipe cleaning and lining relative to the “status quo” scenarios to reduce friction losses and decrease electricity and GHG costs. However, the small variation in capital costs across all scenarios in Table 4-6 suggests that there is an adequate level of installed hydraulic capacity and that adding more capacity does little to reduce frictional energy losses and lower electricity and GHG costs. This observation was verified by conducting additional optimization runs for the PVC and DCLI pipe materials with an objective function (1) that included only capital costs (new pipes, duplicate pipes, and pipe cleaning and lining) and that excluded electricity and GHG costs. In these runs, the capital cost was $968,114 for PVC and capital cost was $1,319,458 for DCLI. The capital costs in these two additional runs are comparable to those found in Scenarios 1-12 of Table 4-6. This suggests that there was adequate installed hydraulic capacity in the Fairfield network and no additional capacity (e.g., new pipes, duplicating existing pipes, and cleaning and lining existing pipes) was needed to offset increases in electricity cost and GHG costs driven by lower discount rates and higher carbon prices. The exclusion of pipe-roughness growth in existing pipes also likely discouraged the addition of duplicate pipes and the cleaning and lining of existing pipes in the Fairfield system.
Other factors likely contributed to the insensitivity of electricity and GHG costs to the discount rate and carbon pricing scenarios considered in the optimization of the Fairfield system. One important factor is the time-declining GHG emission intensity factor used in the analysis. The selection of discounting rate and carbon pricing can have a big impact on the weighting of GHG costs that occur near the end of the 50-year horizon. However, a low GHG emission intensity factor near the end of the 50-y horizon decreased the mass of GHG generated in that period and reduced the ‘weighting force’ of discounting and carbon pricing on GHG costs. Thus the time-declining emission factor adopted in the Fairfield study likely placed a minimal weight on GHG costs in the objective function (1). This is in turn produced solutions with similar capital costs each with minimal levels of pipe duplication and pipe cleaning and lining under all discounting and carbon pricing scenarios.

The selection of a 50-year design horizon may also have played a part in the insensitivity of electricity and GHG costs to discount rate and carbon price. Selecting a design horizon longer than 50 years would likely increase the magnitude and weighting of electricity and GHG costs relative to capital costs in the objective function (1). This would in turn drive the search process to find solutions with varied capital costs and varied levels of pipe duplication and pipe cleaning and lining under different discounting and carbon pricing scenarios.

The final factor to consider was the scope of the optimization problem. The scope of the water distribution expansion problem was limited to include the decision variables of new and duplicate pipe sizing and the cleaning and lining of existing pipes; tank and pump sizing and location were excluded from the optimization problem because no needed pump and tank upgrades were identified in the 50-year planning horizon. Despite this, the inclusion of tanks and pumps in a network often has a large influence over energy use and GHG emissions. Had these additional decision variables been included in the problem, larger variations in capital costs, electricity
costs, and GHG emission costs likely would have been observed across climate change mitigating scenarios.

To meet the Canadian Government’s 2020 emission reduction targets, policy changes in Canada may be centered around revised project discounting practices and a new carbon pricing framework. The Canadian Government has set out to reduce greenhouse gas emissions by 20% below 2006 levels by the year 2020 and by 65% below 2006 levels by the year 2050. In this context, the proposed discount rates and carbon pricing strategies presented in this paper fail to produce the emission-reduction levels set by the Canadian Government in the Fairfield network. Further studies on Canadian water networks are needed to determine the effectiveness of the proposed climate change mitigating strategies.

4.8 Summary and Conclusions
Canada may be moving closer to implementing carbon-mitigation policies that will potentially include an economy-wide cap-and-trade carbon pricing system. This research examined the impact of proposed GHG mitigating strategies in Canada on cost, energy use and greenhouse gas emissions in the design and expansion optimization of the Fairfield water distribution system in Amherstview, Ontario, Canada. The objective of the optimization approach was to minimize the sum of capital costs associated with adding new pipes and cleaning and lining existing pipes, and the electricity and GHG costs associated with pumping water. Results indicated that decreasing the discount rate and moving to a more ambitious carbon pricing trajectory had no significant impact on energy use and mass of GHG emitted in the Fairfield system. Factors that contributed to the insensitivity of energy use and GHG emissions across climate change mitigating scenarios included: 1) adequate hydraulic capacity in the Fairfield system to meet present and future demands, 2) a time-declining emission intensity factor that gave minimal weighting to energy and
GHG costs in the objective function, 3) a relatively short design horizon of 50 years, and 4) the exclusion of decision variables such as tank and pump location and sizing which can have a significant impact on energy use and GHG emissions in networks. The proposed discount rates and carbon pricing strategies presented in this paper failed to produce the emission-reduction levels set by the Canadian Government in the Fairfield network. Further research is needed to determine the effectiveness of the proposed climate change mitigating strategies in other water networks in Canada.

4.9 Acknowledgments
The authors wish to thank David Thompson, P. Eng., M. J. Merritt, P. Eng., and Alex Scott (CTech) at Loyalist Township for their contributions to the development of this paper. This research was financially supported by Queen’s University and the Natural Sciences and Engineering Research Council (NSERC).

4.10 References


Chapter 5
Event-Based Approach to Optimize the Timing of Water Main Rehabilitation with Asset Management Strategies

5.1 Abstract
Municipalities with limited budgets will have to rehabilitate a large stock of deteriorated water mains in the coming decades. There is an opportunity to reduce rehabilitation costs through optimization and asset management strategies. The aim of this paper is to present a new event-based approach to optimize the timing of water main rehabilitation. The approach incorporates a new sparse gene-coding scheme and covers the full range of decision variables such as pipe replacement, pipe duplication, pipe lining, the installation of new pipes, and asset management strategies (e.g., budget constraint and discounts). The new approach was applied to the Fairfield water network. The results suggest that applying a budget constraint prohibited the search process from investing early and heavily in pipe rehabilitation with a resulting increase in cost linked to pipe leakage, pipe breaks, and energy use. Applying discounts decreased capital and operational costs and favored pipe lining over pipe replacement and duplication. A sensitivity analysis showed that water demand, leakage and break growth rates can have a moderate to significant impact on capital and operational costs.

Keywords: water distribution systems, rehabilitation, asset management, multi-objective optimization, pipe breaks, pipe leakage, pipe aging.
5.2 Introduction

Most water distribution systems in North America are old and in need of rehabilitation. An estimated $325 billion is needed to rehabilitate drinking water systems in the United States (Deb et al. 2002) to maintain current service levels. A Canadian study has indicated that $11.5 billion should be spent over the next 15 years to upgrade municipal water distribution systems (CWWA 1997). In North America, water distribution systems lose water at an average rate of 20-50% (Brothers 2001) and at comparable rates in Europe (European Environment Agency 2010). Water loss through leaks and pipe roughness growth in deteriorated pipe account for low pressures, increases in energy costs, and higher repair costs in water distribution networks. Municipalities are faced with the prospect of rehabilitating and replacing a large stock of deteriorated water main assets with capital budgets that are increasingly stretched to their limit. In this context, municipalities have started to examine optimization and asset management strategies as means to reduce the cost of water main asset rehabilitation and replacement.

Research in the last 30 years has focused on developing models to optimize the timing of pipe replacement and rehabilitation in networks. Shamir and Howard (1979) and Walski and Pelliccia (1982) were the first to propose the exponential break model to forecast pipe break rates over a future time horizon. Arulraj and Suresh (1995) developed a significance index to prioritize pipe rehabilitation. Kleiner et al. (1998) proposed a new optimization framework that made use of the exponential break model in which break rate was modeled deterministically as a function of age. In their approach, both network economics and hydraulic capacity were analyzed simultaneously over a pre-defined time horizon. Goulter and Kazemi (1998) studied the effect of spatial and temporal clustering on pipe failure rates. They showed that historical failures in a location of interest are an important predictor of future failures in the same location. Dandy and Engelhardt (2001) applied genetic algorithms (GAs) to optimize the pipe replacement scheduling of the
Adelaide water distribution system and to minimize the overall cost of the project. They showed that GAs are able to identify which pipes to replace when an available budgetary constraint is considered in the decision making procedure. Burn et al. (2003) developed a pipeline asset and risk management system to prioritize the replacement of pipe groups. The model was used to predict failure rates for individual pipes rather than for cohorts of pipes. Nafi et al. (2008) developed a decision support model that considers available financial resources in pipe renewal scheduling. The authors used Cox’s proportional hazard model (PHM) to forecast pipe failure and combined it with multi-objective optimization to enhance the network reliability and reduce failure occurrences.

Multi-objective approaches to optimize the rehabilitation timing of water main assets have also been suggested. Halhal et al. (1999) used a messy genetic algorithm to solve the rehabilitation timing problem. The model was applied to a simple case study in which they maximized benefits of improved system performance and minimized the costs under an available budget constraint. Halhal et al. (1999) also examined the sensitivity of the optimal solution to uncertainties in interest rate and inflation rate. Dandy and Engelhardt (2006) proposed a multi-objective framework to minimize the rehabilitation costs and maximize network reliability simultaneously. In their work, the economic costs of rehabilitation were converted to the present value and reliability was measured as the expected number of customer interruptions per year. Their work provided the starting point that can be extended to include other performance measures which affect customers’ level of service. Dridi et al. (2008) used and compared several evolutionary optimization techniques including IGA, NPGA-II, and NSGA-II to schedule water pipe renewal for short planning periods. Their results confirmed that using evolutionary algorithms could be useful to solve the pipe renewal scheduling problem. In particular, they recommended the use of NSGA-II to optimize large networks. Nafi and Kleiner (2010) developed a model to optimize the
timing of pipe renewal in a distribution network. Their model included discounts that account for the adjacency of infrastructure works to the newly installed pipes and volume discounts on large quantities of purchased pipe for installation in networks. The Nafi and Kleiner (2010) optimization model minimizes cost that include pipe replacement and break repair and maximizes the available budget. The Nafi and Kleiner model does not account for pipe roughness growth and leakage which often drive the search process since the operation cost is often the most significant component of the total cost.

Water distribution system rehabilitation optimization has been addressed in the literature mainly by focusing only on pipe replacement and, in some rare cases, pipe lining. This has been done mostly to simplify what is a complex optimization problem. In reality, utility owners and managers select among a wider decision domain which includes pipe duplication, pipe replacement, a set of pipe lining technologies (e.g., cement-mortar lining, cured-in-place liners), and installing new pipes in areas slated for new growth. Eliminating decision options to simplify the problem sacrifices the practicality of the approach.

Further, previous approaches have attempted to reduce the complexity of the rehabilitation problem by grouping pipes in cohorts or groups and applying replacement scheduling decisions to all pipes in a cohort. In the cohort method, a decision is made for a group of pipes which share some common properties. The number of decisions needed to schedule rehabilitation is fewer in this approach. However, since all pipes in the same group are treated in exactly the same way, these algorithms cannot guarantee that a decision is optimal for each individual pipe in the group.

Another limitation of previous approaches is the assumption that an individual pipe should be replaced strictly if its maintenance cost (e.g., break repair cost) is greater than the replacement cost (Nafi and Kleiner 2010, 2011) without considering system-wide effects. Replacing an
individual pipe strictly based on its maintenance cost and regardless of the effect of this single pipe on the financial analyses of the entire system is neither accurate nor will it guarantee that the final solution will be optimal.

Unlike previous models, the optimization model presented in this paper selects among the fullest range of rehabilitation and/or replacement options that include: the replacement of existing pipes with new pipes, the lining of existing pipes, the duplication of existing pipes while making it possible to apply the fullest range of rehabilitation options to the primary pipe, and the installation of new pipes in new growth areas. Unlike previous models (Nafi and Kleiner 2010, 2011), the model presented in this paper considers the fullest range of commercially-available pipe diameters. The financial and hydraulic performances of each pipe are evaluated annually in the system and in combination with other pipes. Time-varying pipe properties such as the Hazen-Williams ‘C’ factor, break rates, and leakage rates are considered in the model. The model is used to perform an extended period simulation (e.g., 24 hours) in each year of the planning horizon to construct a complete hydraulic ‘picture’ of the system and to better estimate water loss and energy use. The model is used to perform fire simulations at critical nodes in a system at the beginning, middle, and the end of planning period. Previous rehabilitation studies (Halhal et al. 1999, Dandy and Engelhardt 2006, Nafi and Kleiner 2010, Kleiner and Nafi 2011) have not incorporated as extensive a hydraulic analysis as was done in this research.

The paper presents a new event-based multi-objective optimization algorithm that determines the optimal allocation of financial resources and optimal scheduling of water main rehabilitation in water distribution networks. The new optimization model accounts for annual capital and operating budgets and incorporates realistic asset management strategies. The event-based model incorporates a novel sparse gene-coding scheme with small computational and memory requirements that assigns a unique sequence of rehabilitation events (rehabilitation time and type)
to each individual pipe independently of all other pipes in the network. (This is in contrast to previous models where a limited number of rehabilitation schedules are applied to all pipes in an a priori manner.) The model can characterize the hydraulic and cost performance of the unique rehabilitation schedules assigned to each pipe by simulating breaks, leakage, pipe-roughness aging, and hydraulic conditions in the network. The optimization model was applied to the real-world Fairfield water distribution system in southeastern Ontario, Canada, which has approximately 400 pipes and supplies water to approximately 15,000 people. The algorithm was run on a 120 parallel core high performance computing cluster with the Message Passing Interface (MPI) to distribute the computational load among computing nodes (Roshani et al. 2012c).

The chapter is organized as follows. First, the rehabilitation optimization problem is mathematically defined. Second, the Fairfield case study is described. Third, the new algorithm is used to optimize the timing of water main rehabilitation and replacement in the Fairfield system under four asset management scenarios. Fourth, a sensitivity analysis is performed to determine the sensitivity of capital and operational costs to variations in uncertain parameters such as water demand, leakage, and pipe roughness.

5.3 Problem Definition

The multi-objective optimization problem seeks to find the optimal timing of water main rehabilitation and replacement that minimizes the present value of capital and operational costs of the network as detailed in the objective functions (1)-(2). A fast-elitist non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2002) was used to search the large decision space efficiently and minimize two objectives:
\[
\text{Obj1} = \text{Min}(CC) = \text{PV} \left[ \sum_{t=0}^{T} \sum_{p=1}^{np} \left( RC_{t,p} + DC_{t,p} + LC_{t,p} + NP_{t,p} \right) \right]_{DR}
\]

\[
\text{Obj2} = \text{Min}(OC) = \text{PV} \left[ \sum_{t=0}^{T} \sum_{p=1}^{np} \left( LkC_{t,p} + BC_{t,p} \right) + \sum_{t=0}^{T} EC_{t} \right]_{DR}
\]

in which \( CC \) is the capital cost, \( OC \) is the operational cost, \( PV \) is the present value of the costs, \( DR \) is the discount rate, \( t \) is time in years, \( T \) is the planning horizon of the project, \( p \) is the pipe number, \( np \) is the maximum pipe number, \( RC_{t,p} \) is replacement cost for the \( p \)th pipe in the \( t \)th year, \( DC_{t,p} \) is pipe duplication cost, \( LC_{t,p} \) is lining cost, \( NP_{t,p} \) is the new pipe cost, \( LkC_{t,p} \) is the cost of lost water to leakage, \( BC_{t,p} \) is break repair cost, and \( EC_{t} \) is the cost of electricity to pump water. The optimization is also subject to an annual budget constraint such that annual expenditures cannot exceed an annual budget ceiling \( AB_{t} \) for year \( t \) in the planning period. Since the cost of lost water to leakage is not a budget line item, it has been eliminated from the annual costs in the budget constraint (3)

\[
\sum_{p=1}^{np} \left( RC_{p} + DC_{p} + LC_{p} + NP_{p} + BC_{t,p} \right) + EC_{t} \leq AB_{t}
\]

The usual nodal continuity and loop energy conservation constraints are satisfied externally with the network solver EPANET2 (Rossman 2000). The optimization is also subject to minimum pressure and fluid velocity constraints under peak demands. The decision variables are the time, the type, and the place of rehabilitation decisions. Possible types of rehabilitation interventions include the diameter of a pipe being replaced, the diameter of a pipe being duplicated, the diameter of a new pipe in an area slated for future growth, and the type of lining technology used. It also includes the same decisions for the pipe installed as a duplicated pipe.
5.4 Event-Based Rehabilitation: A New Approach to Gene Coding

To simulate a sequence of rehabilitation events for a single pipe in the water main rehabilitation timing problem, the traditional approach is to use one gene to represent each year of the planning horizon. For instance, 50 genes are required to simulate a rehabilitation event in each year of a 50-year planning period in a single pipe. If pipe duplication is also included in the optimization, the number of genes must be doubled to simulate the rehabilitation events linked to the duplicated pipe added in the system. In practice, most of these genes will have zero values in the optimal solution since no rehabilitation activities take place in most years. For example, after replacing an existing pipe with a new pipe, there is typically no need to replace or rehabilitate the pipe for at least another 20-30 years and thus all the genes that represent the intervening 20-30 years are set to zero. This dramatically increases the computational and memory requirements for solving the water main rehabilitation timing problem. Moreover, based on schema theorem (Holland 1992), having these zero-valued (dormant) genes can greatly decrease the speed of convergence to the optimal solutions. This is due to the fact that the zero-valued genes increase the number of decision variables and hence the search space unnecessarily.

![Encoded genes in a chromosome for a single pipe and its duplicate.](image)

*Figure 5.1 Encoded genes in a chromosome for a single pipe and its duplicate.*
The new gene coding adopted in this research is indicated in Figure 5.1. The chromosome structure indicated in Figure 5.1 applies to a single pipe, henceforth called the “main pipe”, and an adjacent duplicate pipe over a fixed planning horizon. A variable called Maximum Number of Events (MNE) represents the maximum number of rehabilitation events expected over the planning period for the main pipe and the duplicate pipe. Considering a lag time of 20-30 years between rehabilitation interventions and a planning horizon of 50 years, typical MNE values could range between 3 and 5. In other words, a pipe and its duplicate could be rehabilitated 3 to 5 times over a 50-year planning horizon.

In Figure 5.1, each rehabilitation event applied to the main pipe and its duplicate (if it is needed) is described with four gene identifiers. The first gene identifier “Event time (main pipe)” denotes the timing of the rehabilitation event applied to the main pipe. The second gene identify “Main pipe event type” denotes the type of rehabilitation applied to the main pipe. The third gene identifier “Event time (duplicate pipe)” denotes the timing of rehabilitation applied to the duplicate pipe. The fourth gene identifier “Duplicate pipe event type” denotes the type of rehabilitation applied to the duplicate pipe. For example, in Figure 5.1 the first rehabilitation event (Event 1) has four gene identifiers. The first gene identifier “9” means that the main pipe is replaced in Year 9 of the planning horizon. The second gene identifier “3” means that the main pipe will be replaced with a new pipe with a new 250 mm diameter. The third and fourth gene identifiers “0” and “0” mean that in Year 0, no duplicate pipe is installed (Do nothing - “0”). In Figure 5.1, for an MNE of 5 events over a 50-year planning horizon, the new gene coding approach of this research produces a chromosome with 20 genes. By comparison, the traditional gene coding method of previous models (Dandy and Engelhardt 2006; Nafi and Kleiner 2010, Kleiner and Nafi 2011) would require 100 genes (2 genes for the main pipe and the duplicate pipe in each year of the 50-year planning horizon). The new approach of this research can thus reduce
the chromosome length by 80% and thus save a significant amount of computer memory and increase the speed of convergence.

5.5 Asset Management Strategies

Budget limitations often force utility decision makers to employ rehabilitation strategies that will allow them to manage their assets in the most cost-effective way. Synchronizing several municipal maintenance projects (e.g., roadwork with pipe replacement and rehabilitation), and aggregating rehabilitation projects together to get a discounted price on materials and labour are two common approaches used to cut costs (Nafi and Kleiner 2010). The new model accounts for savings achieved through synchronizing road reconstruction work with water main replacement or rehabilitation (henceforth called the infrastructure adjacency discount) and discounts achieved on the purchase of large quantities of water main pipe (henceforth called the economies of scale discount). The infrastructure adjacency and economies of scale discounts are indicated in (4)

\[
DAC_p = AdjD_p \times (1 - ConD_p) \times AC_p
\]

in which \( DAC_p \) is the discounted rehabilitation activity cost for pipe \( p \). The actual pipe rehabilitation cost \( AC_p \) in (4) is reduced by the infrastructure adjacency discount, \( AdjD_p \), and the quantity discount \( ConD_p \). The infrastructure adjacency discount \( AdjD_p \) is applied to all water main rehabilitation activities if they are carried out in the same year of road construction or re-construction work in which the pipe is located. The quantity discount \( ConD_p \) is applied to new pipes installed, old pipes replaced, and old pipes duplicated projects completed in the same year and purchased on a volume basis. This means the water main rehabilitation activities should be performed on pipes which have at least one node in common and should occur in the same
year to be considered for quantity discounting (Nafi and Kleiner 2010). The quantity discount is calculated from the schedule in (5)

\[
\text{ConD}_p = \begin{cases} 
0, \ & l_t \leq l_{\min} \\
\frac{\text{ConD}_{\max} (l_t - l_{\min})}{(l_{\max} - l_{\min})}, \ & l_{\min} < l_t \leq l_{\max} \\
\text{ConD}_{\max}, \ & l_{\max} < l_t
\end{cases}
\]  

(5)

in which \( l_t \) is the total pipe length to be replaced or rehabilitated, \( \text{ConD}_{\max} \) is the maximum value of the quantity discount, \( l_{\min} \), \( l_{\max} \) are minimum and maximum pipe length quantities that determine the minimum and maximum quantity discounts, as defined by the supplier (contractor). A graphical illustration of (5) is shown in Figure 5.2. This figure indicates that if the length of pipe to be rehabilitated is less than \( l_{\min} \), the quantity discount is zero. If the length of pipe to be rehabilitated is more than \( l_{\max} \), then the quantity discount is set to its maximum level. If the rehabilitation length falls between \( l_{\min} \) and \( l_{\max} \), the quantity discount will be between 0 and \( \text{ConD}_{\max} \) in (5).

Figure 5.2 Effect of pipe length on quantity discount.
5.6 Model Implementation

The non-dominated sorting genetic algorithm (NSGA-II) was combined with the hydraulic solver EPANET2 (Rossman 2000), a pipe-aging model, a pipe leakage model and a pipe break forecasting model to solve the water main rehabilitation timing problem. Figure 5.3 indicates a flowchart of the OptiNET pipe rehabilitation optimization model which makes use of parallel computing to decrease computational time.

![Flowchart of OptiNET optimization model](image)

*Figure 5.3 Flow chart of OptiNET optimization model.*
In Figure 5.3, an initial random population of solutions is generated. The population of solutions is sent to the hydraulic model, pipe aging, leakage, and pipe break models for hydraulic and economic evaluation. In each year of the planning horizon, the new pipe replacement and rehabilitation activities are applied to the layout of the network. Based on the location and quantity of these new and rehabilitated pipes relative to other public works infrastructure (e.g., roads, other utilities), quantity and infrastructure adjacency discounts in (4)-(5) are calculated. Pipe roughness and pipe leakage are updated with pipe aging and pipe leakage models (discussed below) specified by the user. The EPANET2 hydraulic solver is then run to evaluate the hydraulic performance of the network for the new pipe layout, and the pipe roughness and pipe leakage conditions applied. The break repair cost is estimated for the current year with a break forecasting model specified by the user.

The objective functions (1)-(2) are updated and errors are calculated for the current year. The hydraulic and economic evaluations are repeated in this manner for all n years of the planning period. The objective functions and errors computed over n years of the planning period for all solutions in the population are then used by the NSGA-II to perform crossover, mutation, and selection operations to select the next population of solutions. Successive populations are generated and evaluated until a stopping criterion is satisfied.

### 5.7 Fairfield Water Distribution Network

The Fairfield system provides drinking water to the community of Amherstview and Odessa in southeastern Ontario which have a combined population of approximately 15,000 people. Figure 5.4 indicates the all-pipes model of the system with 405 pipe segments and Table 5-1 indicates the material and age distribution of the pipes in the Fairfield network.
Figure 5.4 Fairfield water distribution system.

PVC pipes were used to replace old pipes or to duplicate them as specified by Loyalist Township. The unit prices of PVC pipes were obtained from a Canadian pipe distributor and are indicated in Table 5-2. Pipe cleaning and cement-mortar lining costs were estimated by inflating costs from Walski (1986) to 2010 dollars. Detailed cost calculations can be found in Roshani et al. (2012a).

Table 5-1 Pipe material and age distribution in Fairfield system.

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Length (m)</th>
<th>Percent of Total Length</th>
<th>Median Pipe Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete (C)</td>
<td>1,342</td>
<td>3.2</td>
<td>1993</td>
</tr>
<tr>
<td>Cast Iron (CI)</td>
<td>10,959</td>
<td>26.4</td>
<td>1965</td>
</tr>
<tr>
<td>Mortar Lined Ductile Iron (DI)</td>
<td>13,388</td>
<td>32.4</td>
<td>1985</td>
</tr>
<tr>
<td>Polyvinyl Chloride (PVC)</td>
<td>15,774</td>
<td>38.0</td>
<td>1999</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>41,464</strong></td>
<td><strong>100.0</strong></td>
<td><strong>1985</strong></td>
</tr>
</tbody>
</table>
Table 5-2 Unit costs of commercially-available PVC pipes and DI pipes cleaning and lining costs (adapted from Walski 1986).

<table>
<thead>
<tr>
<th>Nominal Diameter (mm)</th>
<th>Inside Diameter (mm)</th>
<th>Unit Price ($/m)</th>
<th>Pipe Cleaning and Lining Cost ($/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>160</td>
<td>29</td>
<td>63</td>
</tr>
<tr>
<td>200</td>
<td>210</td>
<td>48</td>
<td>63</td>
</tr>
<tr>
<td>250</td>
<td>258</td>
<td>72</td>
<td>68</td>
</tr>
<tr>
<td>300</td>
<td>307</td>
<td>97</td>
<td>68</td>
</tr>
<tr>
<td>350</td>
<td>356</td>
<td>103</td>
<td>68</td>
</tr>
<tr>
<td>400</td>
<td>404</td>
<td>134</td>
<td>68</td>
</tr>
<tr>
<td>450</td>
<td>453</td>
<td>169</td>
<td>N/A</td>
</tr>
<tr>
<td>500</td>
<td>502</td>
<td>210</td>
<td>N/A</td>
</tr>
<tr>
<td>600</td>
<td>600</td>
<td>304</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The average day demand in the Fairfield network is 32 L/s. The water demand at the end of the 20-year planning horizon was projected with annual growth rates reported in Table 5-3 and provided by Loyalist Township (CH2M Hill 2007). Two future network expansions are planned by Loyalist Township. The first expansion located in the western part of the network (indicated in Figure 5.4 as a grey-shaded area) will be completed in the first 10 years of the planning period and the second expansion, located in the northern part of the network, will be completed at the end of the 20-year planning horizon. Loyalist Township has an annual budget of $850,000 / yr for capital and operational expenditures (Thompson 2011).

The hydraulic performance (maximum velocity and minimum pressure limit) of the Fairfield network was evaluated under average day and peak demands. The maximum velocity constraint was evaluated under maximum hour and/or maximum day + fire demand for each year of the 20-year rehabilitation planning period. Average day demand was modeled as an extended period simulation (EPS) for 24 hours with an average day diurnal pattern. The average day demand EPS was performed for each year of the planning period. Maximum hour demand simulations were
performed at Year 0, Year 10, and Year 20 of the planning period. Maximum day + fire simulations were performed and pressures were observed at 2 critical nodes (J-514 and J-551 in Figure 5.3) at Years 0, 10, and 20. A needed fire flow of 33 L/s was adopted in accordance with Fire Underwriters Survey (FUS) guidelines (FUS 1999). Therefore the hydraulic conditions of each solution was evaluated on the basis of twenty 24-hour extended period simulations, three maximum hour demand simulations, and six maximum day demand + fire simulations.

Table 5-3 Projected annual growth rates and current and projected water demands in the Town of Amherstview.

<table>
<thead>
<tr>
<th>Water Use</th>
<th>Land Use (%)</th>
<th>Annual Growth Rate (%)</th>
<th>2010 Present Water Demand (L/s)</th>
<th>2030 Projected Water Demand (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>68</td>
<td>3.5</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Multi-residential</td>
<td>18</td>
<td>3.5</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Commercial</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Institutional</td>
<td>8</td>
<td>2</td>
<td>2</td>
<td>3.7</td>
</tr>
<tr>
<td>Industrial</td>
<td>10</td>
<td>1</td>
<td>3</td>
<td>4.1</td>
</tr>
<tr>
<td>New Industrial</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>8.8</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td></td>
<td>32</td>
<td>70.6</td>
</tr>
</tbody>
</table>

5.7.1 Pipe Leakage Model

A number of models have been proposed in the literature to forecast leakage in deteriorated pipes. Among these models, the approach by Germanopoulos (1985) that was later adapted by Alvisi et al. (2009) was used in this study to forecast water loss in the Fairfield network. This approach was selected for its simplicity and its accuracy in estimating lost water and for its parsimonious data requirements. The approach assumes that the leak area (percent of the pipe wall surface area) increases over time as a function of pipe age and that it follows an exponential trend as in (6)
\( \Omega = \pi d_p^2 l_p \nu e^{\beta t} \) \hspace{1cm} (6)

in which \( \Omega \) is the percent of open surface area in a pipe, \( \pi = \text{pi constant} \), \( d_p = \text{pipe diameter} \), \( l_p = \text{pipe length} \), \( \nu \) and \( \beta \) are two exponential components, and \( t = \text{pipe age (year)} \). While \( \nu \) and \( \beta \) may vary with pipe diameter and material and even the type of pipe installation (Martinez et al. 1999), they have been assumed to be the same for all pipe segments in the Fairfield system since there is no data available for these variables. (It is noted that both these variables are subject to a sensitivity analysis presented later in this paper.) Both of these variables were calibrated based on water loss measurements provided by Loyalist Township. The calibration was performed for the period 1998-2003 in which no rehabilitation activities (pipe replacement and lining) were reported. The calibrated leak model parameters were found to be \( \nu = 4 \times 10^{-7} \) and \( \beta = 0.13 \) for the Fairfield network.

5.7.2 Break Model

A total of 94 pipe break incidents were reported by Loyalist Township in the period 1982-2011. Break distribution by pipe material is indicated in Table 5-4. The time-exponential break model of Shamir and Howard (1979) was used to project the number of breaks in each pipe. The Shamir and Howard (1979) forecasting model was used in this research because it is practical and has been used extensively in the past to generate reasonable forecasting results. This model assumes that number of breaks will increase exponentially with pipe age as in (7).

\[ \text{Nbr} = \alpha_0 e^{\beta t} \] \hspace{1cm} (7)

in which \( \text{Nbr} \) is the future break rate, \( \alpha_0 = \text{initial break rate (break/year/km)} \), \( \beta = \text{break growth rate (break/year)} \), and \( t = \text{time (year)} \). The values of \( \alpha_0 \) and \( \beta \) were calculated for cast iron (CI) and ductile iron (DI) pipe materials based on the records provided by Loyalist
Township. Break records for Asbestos Cement (AC) and Polyvinyl Chloride (PVC) pipes were scarce and so values near the lower limit of the proposed range in the literature were assumed for $\alpha_0$ and $\beta$ in AC and PVC pipes (Shamir and Howard 1979; Walski and Pelliccia 1982; Kleiner and Rajani 1999; Mailhot et al. 2003). The effects of these values on the Pareto front were also examined in the sensitivity analysis of the paper. Table 5-4 indicates the calibrated and assumed values for the pipe break exponential models applied to the Fairfield system.

Table 5-4 Break distribution by pipe material and exponential model values.

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>No. Breaks</th>
<th>Pipe Age at Time of Break (years)</th>
<th>Break Exponential Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>Avg.</td>
</tr>
<tr>
<td>DI</td>
<td>21</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>CI</td>
<td>65</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>PVC</td>
<td>6</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>AC</td>
<td>2</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Total</td>
<td>94</td>
<td>3</td>
<td>32</td>
</tr>
</tbody>
</table>

5.7.3 Pipe Roughness Growth Model

The roughness growth model of Sharp and Walski (1988) has been used extensively in the research literature to forecast reductions in the Hazen-Williams ‘C’ factor in aging pipe. Since the Sharp and Walski (1988) roughness growth model is unique in the literature, it was adopted in this study to forecast Hazen-Williams ‘C’ factors in CI and DI pipes in the Fairfield network. Flow test data were used to estimate the Hazen-Williams ‘C’ factor values of existing water mains in the network (CH2M Hill 2007). Average ‘C’ factor values of 55 for cast iron, 120 for concrete, 120 for ductile iron and 150 for PVC pipes were found. Given the inability of the Sharp and Walski model to forecast roughness growth in PVC and AC pipe, the ‘C’ factors for these
pipe materials were assumed constant for the planning period. The assumption of constant ‘C’ is a
conservative assumption with respect to energy use.

5.8 Asset Management Scenarios and Results
Four scenarios were defined to investigate the impact of different water main asset management
strategies on capital and operational costs in the Fairfield network. In Scenario 1 (Scn. 1), both
infrastructure adjacency and quantity discounts were applied in conjunction with the annual
budget constraint. In Scenario 2 (Scn. 2), the discounts were applied while the annual budget
constraint was not applied. In Scenario 3 (Scn. 3), both the adjacency and quantity discounts and
the annual budget constraint were not applied. In Scenario 4 (Scn. 4), the infrastructure adjacency
and quantity discounts were not applied, while the budget constraint was applied.

5.8.1 Pareto-Fronts of Scenarios 1 Through 4
The Pareto fronts generated in the four scenarios are indicated in Figure 5.5. This figure indicates
that the Scenario 2 front (discounts applied, budget constraint not applied) has the lowest capital
cost and operational costs, while the Scenario 4 front (discounts not applied, budget constraint
applied) has the highest costs. The application of the budget constraint and the adjacency and
quantity discounts largely accounts for the difference in cost between these two fronts. Scenario 2
has low capital costs because it benefits from adjacency and quantity discounts, while Scenario 4
has higher capital costs because no such discounts are available. The removal of the budget
constraint in Scenario 2 allows the optimization engine to make “up-front” capital investments to
replace and rehabilitate the large stock of old, deteriorated water mains in the Fairfield system.
This “up-front” capital investment at the beginning of the planning period is not capped by the
budget constraint and allows the municipality to lower operational costs in the system in
subsequent years – mostly from reduced leakage and reduced energy use for pumping.
Conversely, applying the budget constraint in Scenario 4 limits the “up-front” capital investments to the available annual funds (as set by the budget). The rehabilitation of the old, deteriorated stock of pipes must be deferred to subsequent years which increases operational costs from leakage loss and pumping.

Figure 5.5 Pareto fronts generated in asset management Scenarios 1 through 4.

The capital and operational costs of solutions located at opposite ends of the Pareto fronts in Figure 5.5 were examined and compared. In Figure 5.5, select solutions in distinct regions of each Pareto front are indicated with a circle. These solutions are the minimum capital cost solutions (left side of fronts), the minimum operational cost solutions (right side of fronts), and the minimum total cost solutions (at or near the elbow of the fronts). In Table 5-5, the minimum capital cost solution is identified with the hyphenated identifier “-1” (e.g., Scn. 1-1), the
minimum operational cost solution is identified with “-2” (e.g., Scn. 1-2), and the minimum total cost solution is identified with “-3” (e.g., Scn. 1-3).

Table 5-5 Average annual costs, present value capital costs, present value operational costs, and present value total cost for asset management Scenarios 1 through 4.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Adjacency Discount</th>
<th>Quantity Discount</th>
<th>Budget Limit</th>
<th>Average Annual Cost ($1,000)</th>
<th>PV Capital Cost (SM)</th>
<th>PV Operational Cost (SM)</th>
<th>PV Total Cost (SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Break</td>
<td>Leak</td>
<td>Energy</td>
<td>Break</td>
<td>49.5</td>
<td>276.6</td>
<td>44.9</td>
</tr>
<tr>
<td>Scn. 1-1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scn. 1-2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>29</td>
<td>174.8</td>
<td>43</td>
<td>4.35</td>
</tr>
<tr>
<td>Scn. 1-3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>38.6</td>
<td>218.6</td>
<td>43.7</td>
<td>3.52</td>
</tr>
<tr>
<td>Scn. 2-1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>63.8</td>
<td>366.4</td>
<td>45.4</td>
<td>3.05</td>
</tr>
<tr>
<td>Scn. 2-2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>17.4</td>
<td>82.9</td>
<td>40</td>
<td>4.52</td>
</tr>
<tr>
<td>Scn. 2-3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>15.8</td>
<td>101.3</td>
<td>39.3</td>
<td>3.81</td>
</tr>
<tr>
<td>Scn. 3-1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>56.5</td>
<td>379.5</td>
<td>46</td>
<td>3.11</td>
</tr>
<tr>
<td>Scn. 3-2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>19.1</td>
<td>103.2</td>
<td>39.2</td>
<td>5.45</td>
</tr>
<tr>
<td>Scn. 3-3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>24.1</td>
<td>121.9</td>
<td>40.2</td>
<td>4.03</td>
</tr>
<tr>
<td>Scn. 4-1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>59.5</td>
<td>379.4</td>
<td>46.5</td>
<td>3.29</td>
</tr>
<tr>
<td>Scn. 4-2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>34.2</td>
<td>196.8</td>
<td>42.3</td>
<td>4.66</td>
</tr>
<tr>
<td>Scn. 4-3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>37.1</td>
<td>226.7</td>
<td>44.4</td>
<td>3.72</td>
</tr>
</tbody>
</table>

1. $M = millions of dollars
2. Scn. 1-1 denotes the minimum capital cost solution on the Scenario 1 front (from Figure 5.5).
3. Scn. 1-2 denotes the minimum operational cost solution on the Scenario 1 front (from Figure 5.5).
4. Scn. 1-3 denotes the minimum total cost solution on the Scenario 1 front (from Figure 5.5).

Table 5-5 indicates that minimum capital cost solutions (“-1”) have higher average annual operational costs (break repair, leakage, and energy) than minimum operational cost solutions (“-2”). This is owing to the fact that in minimum capital cost solutions (“-1”), the search process makes minimal capital investments to replace and rehabilitate the old CI pipe stock in the Fairfield network to keep the capital costs low. As a result, the unimproved CI pipe stock breaks frequently, has a high leakage level, and induces high frictional losses in the system which account for the high annual operational costs. By contrast, in minimum operational cost solutions
continuous investments in rehabilitation are made throughout the planning period to keep operational costs low.

5.8.2 Impact of the Budget Constraint and Discounts on Capital and Operational Costs
The influence of the budget constraint on average annual costs (breaks, leaks, and energy) in the four scenarios was examined. Scenario 1 where the budget constraint is imposed was compared to Scenario 2 where it is not (both scenarios include adjacency and quantity discounts). The results in Table 5-5 suggest that average annual costs of break repair, energy, and leakage are higher in Scenario 1 than in Scenario 2 for minimum capital cost solutions (“-1”), minimum operational cost solutions (“-2”), and minimum total cost solutions (“-3”). Similar results are found by comparing Scenario 4 (budget constraint applied) to Scenario 3 (no budget constraint applied) in Table 5-5. Removing the budget constraint allows the search process to make “up-front” capital investments to replace and rehabilitate the large stock of old, deteriorated CI water mains in the Fairfield system. This “up-front” capital investment at the beginning of the planning period allows the municipality to lower operational costs in the system in subsequent years – mostly from reduced leakage and reduced energy use for pumping.

The influence of the adjacency and quantity discounts on average annual costs (break, leaks, and energy) as well as on present value capital costs and operational costs was also examined. By comparing minimum total cost solutions (“-3”) in Table 5-5, the adjacency and quantity discounts of Scenarios 1 and 2 produce lower present value capital costs and operational costs than Scenarios 3 and 4 where no discounts are applied. This is due to the fact that applying the quantity and adjacency discounts in Scenarios 1 and 2 reduces the present value capital costs of rehabilitation relative to Scenarios 3 and 4 and part of these savings are applied to the replacement and rehabilitation of additional pipes. For example, the total length of pipes replaced
in the minimum total cost solution of Scenario 1 (Scn. 1-3) is 43,593 m while the replaced length in the minimum total cost solution of Scenario 4 (Scn. 4-3) is 41,735 m. The added replacement activities further decreases operational costs associated with water loss, energy use, and break repair in Scenarios 1 and 2.

5.8.3 Impact of Discounts on the Geographic Location of Rehabilitated Pipe

The impact of adjacency and quantity discounts on the location of rehabilitation activities was also examined. Figure 5.6 indicates the location of rehabilitated pipes that benefit from discounts in the minimum total cost solution of Scenario 1 (Scn. 1-3) where the budget constraint and discounts are applied, and in the minimum total cost solution of Scenario 4 (Scn. 4-3) where the budget constraint is applied but no discounts are applied. In Scenario 1, newly installed pipes that benefit from the quantity discount are mainly located in the future growth areas while the rehabilitated pipes (replaced, relined, or duplicated) that benefit from the adjacency discount are located in the old section of Fairfield in close proximity to the aging pipes and roads in need of repair. In Scenario 4 where no discounts are applied, the location of rehabilitated pipes which could hypothetically benefit from adjacency and quantity discounts are distributed across the network.
Figure 5.6 Location of pipes that benefit from: a) adjacency and quantity discounts in Scenario 1 (Scn. 1-3), and b) adjacency and quantity discounts in Scenario 4 (Scn. 4-3).
5.8.4 Impact of Budget Constraint and Discounts on the Occurrence of Rehabilitation Events

The impact of the budget constraint and discounts on the length and age of rehabilitated pipes was examined. Table 5-6 indicates the length and average age of pipes replaced, duplicated, and relined in the minimum total cost solutions (“-3”) for the four asset management scenarios. Table 5-6 indicates that when the budget constraint is applied, the length of pipe replaced decreases by 2,915~7,312 m, the length of pipe duplicated decreases by 349-691 m, and the length of pipe relined decreases by 1,415-1,422 m. This is owing to the fact that the budget constraint limits the funds available and the amount of pipe that can be rehabilitated in any given year. Table 5-6 suggests that applying the budget constraint increases the average replacement age by 1.2-1.6 years, the average duplication age by 0.4-2.5 years, and the average lining age by 2.2-7.5 years. This result suggests that the budget constraint prohibits the search process from investing early and heavily in pipe rehabilitation and that this deferment lengthens the age at which old pipes are replaced, duplicated, and relined.

The application of discounts decreased the replacement and duplication activities and increased pipe lining activities in the system. Table 5-6 indicates that applying the discounts decreased the replacement length by 4,062 m (moving from Scenario 3 and 2) and slightly increased it by 335 m (moving from Scenario 4 to 1). Further, applying discounts decreased the duplication length by 121-463 m, and led to a 2,042-2,049 m increase in pipe lining. This is owing to the fact that the search process chose to invest the savings achieved with the discounts to increase the length of pipe relined – a less expensive option than pipe replacement and pipe duplication. Further, applying the discounts tended to decrease the pipe age at replacement by 0.3-0.7 years, to decrease the pipe age at duplication by 1.5-3.6 years, and to decrease pipe age at lining by 3.3 years (the lining age increases by 2 years when moving from Scenario 3 to 2). Not surprisingly,
Table 5-6 also indicates that including discounts increases the percent of rehabilitated pipes which benefit from these discounts. Since discounts were not applied in Scenarios 3 and 4, the percent of pipes that benefit from discounts (indicated in grey in Table 5-6) is a theoretical number that represents the percent of pipes that would have benefited had discounts been included in these two scenarios.

Table 5-6 Main length rehabilitated, age of rehabilitation, and percent of mains that benefit from discounts in the asset management Scenarios 1-4.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Adjacency and Quantity Discounts</th>
<th>Length (m) and Percent of Total (m)</th>
<th>Avg. Age of Rehab. (Year)</th>
<th>Adjacency Discount (%)</th>
<th>Quantity Discount (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scn. 1-3</td>
<td>X</td>
<td>43,593 (64.8)</td>
<td>31.7</td>
<td>5.6</td>
<td>13.8</td>
</tr>
<tr>
<td>Scn. 2-3</td>
<td>X</td>
<td>46,508 (64.4)</td>
<td>30.5</td>
<td>7.4</td>
<td>15.9</td>
</tr>
<tr>
<td>Scn. 3-3</td>
<td>X</td>
<td>50,570 (68)</td>
<td>30.8</td>
<td>4.04</td>
<td>7.4</td>
</tr>
<tr>
<td>Scn. 4-3</td>
<td>X</td>
<td>43,258 (66.2)</td>
<td>32.4</td>
<td>2.7</td>
<td>8.1</td>
</tr>
<tr>
<td>Pipe Duplication</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scn. 1-3</td>
<td>X</td>
<td>10,723 (15.9)</td>
<td>27.6</td>
<td>1.3</td>
<td>5.3</td>
</tr>
<tr>
<td>Scn. 2-3</td>
<td>X</td>
<td>11,414 (15.8)</td>
<td>27.2</td>
<td>0</td>
<td>6.3</td>
</tr>
<tr>
<td>Scn. 3-3</td>
<td>X</td>
<td>11,535 (15.5)</td>
<td>28.7</td>
<td>0.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Scn. 4-3</td>
<td>X</td>
<td>11,186 (17.1)</td>
<td>31.2</td>
<td>0.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Pipe Relining</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scn. 1-3</td>
<td>X</td>
<td>12,936 (19.2)</td>
<td>31.2</td>
<td>2.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Scn. 2-3</td>
<td>X</td>
<td>14,351 (19.9)</td>
<td>29</td>
<td>3.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Scn. 3-3</td>
<td>X</td>
<td>12,309 (16.5)</td>
<td>27</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Scn. 4-3</td>
<td>X</td>
<td>10,887 (16.7)</td>
<td>34.5</td>
<td>1.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

1. The “-3” identifier denotes the minimum total cost solution.
2. Denotes the percent of mains that benefit from the adjacency of infrastructure discount. This statistic is calculated as: (length of mains that benefit from adjacency of infrastructure discount) / (total length of main rehabilitated).
3. Denotes the percent of mains that benefit from the quantity discount. This statistic is calculated as: (length of mains that benefit from quantity discount) / (total length of main rehabilitated).
4. The grey area denotes the percent of mains that could hypothetically have benefited from asset management strategies had discounts been applied.
5.8.5 Impact of Budget Constraint on the Annual Costs

The impact of the budget constraint on the time variation of annual costs (leaks, breaks, and energy) was examined. Figure 5.7 indicates the time variation of annual costs for the minimum total cost solutions (“-3”) in Scenarios 1 through 4. (The budget constraint of $850,000 is also indicated in this figure.) Figure 5.7 shows that in Scenarios 2 and 3 (budget constraint not applied), the annual cost is allowed to exceed the $850,000 limit in Year 1 and in Years 19 and 20. Figure 5.7 also indicates that these two scenarios have among the lowest annual costs in the middle period (Years 8-15) of the planning horizon.

![Figure 5.7 Time variation of annual total cost (capital cost + operational cost) for the minimum total cost solutions in Scenarios 1 through 4.](image)

Conversely, in Scenarios 1 and 4 (budget constraint applied), annual costs never exceed the $850,000 limit and are consistently higher than those of Scenarios 2 and 3 in the middle period. Removing the budget constraint allows for “up-front” replacement and rehabilitation of deteriorated pipe which has the effect of reducing annual costs later in the planning period. The impact of the budget constraint on the time variation of annual leak volumes was also examined. Figure 5.8 indicates the time variation of annual leak volume for the minimum total cost solution in Scenarios 1-4. Figure 5.8 suggests that the annual leak volume is higher in Scenarios 1 and 4.
(where the budget constraint was applied) than in Scenarios 2 and 3 (where the budget constraint was not applied). This is explained by the fact that removing the budget constraint allows the optimization engine to make “up-front” investments in pipe replacement and rehabilitation above and beyond the $850,000 ceiling at the beginning of the planning period to reduce leakage later into the planning period. Similarly, an analysis of the time variation of breaks suggest that removing the budget constraint allows the search process to make “up-front” investments in pipe replacement and rehabilitation that lower pipe breaks and repair costs for the duration of the planning period.

Figure 5.8 Time variation of annual leak volume for minimum total cost solutions in Scenarios 1 through 4.

The impact of the budget constraint on the time variation of annual energy costs was also examined. The results suggest that applying the budget constraint did not create any significant differences in annual energy costs across the four scenarios. The similarity in energy use and energy costs across the scenarios is owing to the fact that the majority of pumping energy is used to lift water over the height of 49 m to the elevated tank T-1 in the Fairfield network in Figure 5.4.
5.9 Sensitivity Analysis

The analysis of the asset management scenarios suggests that the main drivers of cost were water demand, leakage, and pipe breaks. A sensitivity analysis was performed to examine the sensitivity of the capital and operational costs to uncertainties in forecasted water demand, initial break rate, break growth rate, initial leak rate, leak growth rate, and Hazen-Williams ‘C’ factor. The main result from this sensitivity analysis suggests that water demand, leakage growth rate, and break growth rate can have a moderate to significant impact on capital and operational costs. Specifically, a 15% increase in water demand produces a 15.4% increase in present value capital cost and a 7.4% increase in operational cost. A 15% increase in leak growth rate produces a 15.4% in present value capital cost and a 100% increase in present value operational cost. Further, a 15% increase in break growth rate produces a 2.6% increase in present value capital cost and a 14.8% increase in present value operational cost. Generally, to meet higher demand, leakage, and break levels, the search process selects solutions with more installed hydraulic capacity by replacing pipes, duplicating pipes, and installing new pipes in growth areas to reduce costs linked to breaks, leakage, and energy use.

The projected water demand could be reduced through water conservation incentives in the future therefore this parameter is increased and decreased by 15%. Hazen-Williams coefficients are only decreased by 15% to be in conservative side. Moreover the leak and break coefficients are increased by 15%. The goal of this sensitivity analysis is to understand how uncertain variables can affect final solutions which are on the trade off curve. These variation levels are chosen based on engineering judgment.

It is a controversial issue to select one solution from a trade off curve to compare various runs. Therefore the mean and standard deviations of objectives and all of their components (i.e. the water lost cost, break repair cost, energy cost, pipe replacement cost, etc.) were calculated for all
of the solutions in the final generation of each run. The results were compared with the status quo (Scenario 3 in which neither budget limit nor discounts were applied).

Table 5-7 The results of sensitivity analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scenario</th>
<th>-15% Future Demand</th>
<th>+15% Future Demand</th>
<th>+15% Initial Leak</th>
<th>+15% Leak Growth Rate</th>
<th>+15% Initial Break</th>
<th>+15% Break Growth Rate</th>
<th>-15% Hazen-Williams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost ($M)</td>
<td>S-3 No Disc, No Budget</td>
<td>3.9 (0.47)</td>
<td>4.5 (0.37)</td>
<td>3.9 (0.44)</td>
<td>4.2 (0.46)</td>
<td>4.5 (0.39)</td>
<td>3.9 (0.37)</td>
<td>4.0 (0.43)</td>
</tr>
<tr>
<td></td>
<td>Average Annual Pipe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replacement Cost ($1,000)</td>
<td></td>
<td>231.3 (39.3)</td>
<td>281.5 (34.2)</td>
<td>238.1 (39.6)</td>
<td>242.2 (38.4)</td>
<td>266.2 (31.6)</td>
<td>238.8 (32.1)</td>
<td>246.4 (38)</td>
</tr>
<tr>
<td>Average Annual Lining Cost ($1,000)</td>
<td></td>
<td>47.2 (6.6)</td>
<td>39.5 (6.2)</td>
<td>48.8 (7.1)</td>
<td>48.2 (6.8)</td>
<td>43.9 (7.3)</td>
<td>43.8 (6.4)</td>
<td>44.5 (7.1)</td>
</tr>
<tr>
<td>Average Annual Pipe Duplication Cost ($1,000)</td>
<td></td>
<td>72.9 (13.1)</td>
<td>68.3 (12)</td>
<td>59.3 (10)</td>
<td>74.8 (12.7)</td>
<td>85.4 (15.9)</td>
<td>66.1 (12.1)</td>
<td>68.4 (13.4)</td>
</tr>
<tr>
<td>Average Annual New Pipe Installation Cost ($1,000)</td>
<td></td>
<td>27.9 (3.6)</td>
<td>31.6 (3.4)</td>
<td>27.2 (5.6)</td>
<td>26.2 (4.1)</td>
<td>30.5 (4.3)</td>
<td>26.9 (3.5)</td>
<td>25.6 (4)</td>
</tr>
<tr>
<td>Operational Cost ($M)</td>
<td></td>
<td>2.7 (0.72)</td>
<td>2.9 (0.45)</td>
<td>2.6 (0.85)</td>
<td>3 (0.6)</td>
<td>5.4 (1)</td>
<td>2.8 (0.54)</td>
<td>3.1 (0.68)</td>
</tr>
<tr>
<td>Average Annual Lost Water Cost ($1,000)</td>
<td></td>
<td>195.2 (74.2)</td>
<td>195 (47.6)</td>
<td>203.7 (87.7)</td>
<td>215.1 (62.8)</td>
<td>425.3 (110.5)</td>
<td>193.6 (54.9)</td>
<td>178.6 (56.2)</td>
</tr>
<tr>
<td>Average Annual Energy Cost (1,000$)</td>
<td></td>
<td>42.2 (2.1)</td>
<td>46.4 (1.6)</td>
<td>39.3 (2.7)</td>
<td>42.8 (1.8)</td>
<td>48.6 (2.6)</td>
<td>42.9 (1.7)</td>
<td>42.5 (1.7)</td>
</tr>
<tr>
<td>Average Annual Break Repair Cost (1,000$)</td>
<td></td>
<td>33.5 (11.8)</td>
<td>36.6 (8.7)</td>
<td>36 (16.5)</td>
<td>32.9 (9.1)</td>
<td>27.6 (5.9)</td>
<td>39.2 (10.8)</td>
<td>74.4 (28.7)</td>
</tr>
</tbody>
</table>

(1) Million Dollars
(2) The first number is the mean value and the second number is the standard deviation

Table 5-7 presents the results of sensitivity analysis. The first number in each cell is the average value and the number in the parenthesis is the standard deviation of the values. The results indicated that the projected future demand and leak growth rate are the most sensitive parameters which affected the capital cost. 15% increment in either of these values increases the capital cost by 15.4%. Increasing the future demand increases the investment in the pipe replacement by 21% and decreases both lining and pipe duplication while increasing the leak growth rate increases the replacement and duplication by 15% and 17% respectively. This is mainly because increasing the leak growth rate increases the operational cost dramatically (approximately 100%) while the future demand increases it only 7.4%. To reduce the operational cost the OptiNet attempts to reduce the leak by a) replacing old pipes with new ones and b) decreasing the dynamic head of the system by increasing the network capacity using pipe duplications.
Decreasing the projected future demand by 15% had no impact on the capital cost and it slightly increased the operational cost. This is owing to the fact that most of the pipes in the Fairfield WDS are old and in need to be replaced therefore investment in pipe replacement and lining stay almost the same as before while the pipe duplication investment decreases because there is no need to increase the system capacity. Increasing the initial leak rate increases the operational cost and to reduce this cost the OptiNet increases the investments in pipe replacement, lining and duplication.

Although increasing in the pipe roughness did not affect the capital cost but it changes the distribution of investments among rehabilitation options. It decreases the duplication investment by 13% and uses the saved money to increase pipe replacement by 5%. In this way the optimizer can decrease the operational cost while it keeps the energy cost without increasing. And finally, increment in initial break rate and break growth rate can dramatically increase the break repair cost. To decrease this cost the optimizer encourages the solutions which invest more in the pipe replacement and reduces the lining and duplication investment.

5.10 Summary and Conclusions
The paper has presented a new event-based approach to optimize the timing of water main rehabilitation and replacement in water distribution networks. The approach was applied to the Fairfield water network to examine the impact of asset management strategies (applying a budget constraint and discounts) on the capital and operational costs of rehabilitation solutions. The results suggested that applying a budget constraint prohibited the search process from investing early and heavily in pipe rehabilitation; the resulting postponement of pipe rehabilitation increased operational costs linked to leakage, breaks, and energy use in old, unimproved pipes. The results also suggested that applying discounts decreased capital and operational costs and
favored pipe lining over pipe replacement and duplication. A sensitivity analysis showed that water demand, leakage growth rate, and break growth rate can have a moderate to significant impact on capital and operational costs.

5.11 Acknowledgements

The authors thank David Thompson, P. Eng. at Loyalist Township for providing data in the development of this paper. This research was financially supported by Queen’s University and the Natural Sciences and Engineering Research Council.

5.12 References


Adjacency of Infrastructure Works and Economies of Scale” *Journal of Water Resources 
Planning and Management*, 136(5), 519-530.

Mitigation Strategies on the Optimal Design and Expansion of the Fairfield, Ontario Water 
Network: A Canadian Case Study” *Journal of Water Resources Planning and 
Management*, 138(2), 100-110.

Systems Under Climate Change Mitigation Scenarios” *2012 World Environmental and 
Water Resources Congress*, Albuquerque, New Mexico, USA.

Distribution Network Optimization.” *2012 Water Distribution System Analysis Conference*, 
Adelaide, Australia. 28-35.


American Water Works Association*, 80(11), 34-40.


Chapter 6

Water Distribution System Rehabilitation under Climate Change Mitigation Scenarios in Canada

6.1 Abstract

Many countries are considering policy instruments such as a carbon tax and economic discounting to reduce greenhouse gas (GHG) emissions in key sectors like the water sector. The research examines the impact of economic discounting and a carbon tax on the optimization of water main rehabilitation. A new pipe rehabilitation optimization algorithm that accounts for GHGs was developed and applied to the Fairfield water distribution system in Amherstview, Ontario, Canada. Here, adopting a low discount rate and levying a carbon tax had a small impact in reducing energy use and GHG emissions and a significant impact in reducing leakage and pipe breaks. Further, a low discount rate and a carbon tax encouraged the search process to invest in rehabilitation early in the planning period to reduce continuing leakage, pipe repair, energy, and GHG costs. A sensitivity analysis suggested that water demand and leakage growth rate had a moderate to significant impact on the present value of capital and operational costs and on GHG emissions in the Fairfield system.

Keywords: water distribution systems, water main rehabilitation, multi-objective optimization, climate change, carbon tax, discount rate, energy use.

6.2 Introduction

Meeting an increased demand for clean water, adapting water systems to be more resilient to anticipated changes in climate, and reducing greenhouse gas (GHG) emissions are the great challenges which water managers face over the coming decades. Reducing GHGs across
economic sectors has been recognized as a valuable tool to mitigate unacceptable physical and economic damages linked to a future change in climate (Stern et al. 2006). The water sector is a heavy consumer of electricity for raw water pumping in transmission systems and for pumping treated drinking water in distribution networks. For example in the UK, roughly 3% of generated electricity is consumed by the water industry (Ainger et al. 2009). Approximately 4% of electricity produced in the U.S. is used to transport and treat water (Goldstein and Smith 2002).

At the same time, many water distribution networks are aging. Buried water mains in many systems are experiencing high break and leakage rates, loss of hydraulic capacity, and water quality problems (Canadian Infrastructure Report Card 2012; ASCE 2009). Significant leakage rates ranging from 10% to 50% have been reported in European cities (European Environment Agency 2010). In North America, the average reported leakage rate is estimated to range between 20% and 30% (Brothers 2001). Replacing and rehabilitating old water mains presents an opportunity to reduce energy use and GHGs linked to water distribution through the reduction of leakage, breaks, and energy frictional losses in aging systems. For example, Arai (2012) reported that a leak-reduction program implemented in the City of Tokyo reduced CO$_2$ emissions by 67,100 tonnes/year.

### 6.2.1 Greenhouse Gas Emissions, Carbon Tax, and Economic Discounting in Canada

Many governments have begun or are planning to use economic instruments such as discounting, levying carbon taxes, and introducing carbon cap-and-trade structures to encourage large economic sectors—including the water sector—to reduce their GHG emissions and mitigate the effects of climate change. In Canada, adopting a carbon tax and lowering discount rates for public project planning are two strategies that have been proposed to reduce GHGs in the Canadian economy (NRTEE 2009). This research will examine the impact of these two carbon mitigating
strategies on the water main replacement and rehabilitation planning of a Canadian water
distribution network.

To achieve GHG emission reduction targets for 2020 and 2050 set by the Government of Canada,
the National Round Table on the Environment and the Economy (NRTEE) proposed a carbon tax
policy (NRTEE 2009). This policy suggests that a “Fast and Deep” carbon tax trajectory (Table
6-1) is required to change economic behavior at the level sufficient to achieve the mid-term and
long term carbon-reduction goals to reduce GHGs to 20% below 2006 levels by 2020 and 60-
70% below 2006 levels by 2050. The NRTEE has also acknowledged that a less aggressive
carbon tax trajectory “Slow and Shallow” (Table 6-1) could be expected if Canada were to
engage in international carbon trading (NRTEE 2009). The research will examine the effect of
both carbon tax trajectories on water main replacement and rehabilitation planning decisions
taken in a Canadian water distribution network.

Table 6-1 NRTEE carbon tax trajectories. (NRTEE 2009)

<table>
<thead>
<tr>
<th>Year</th>
<th>No Tax</th>
<th>Slow and Shallow</th>
<th>Fast and Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>2020</td>
<td>0</td>
<td>30</td>
<td>75</td>
</tr>
<tr>
<td>2025</td>
<td>0</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>2030</td>
<td>0</td>
<td>75</td>
<td>225</td>
</tr>
<tr>
<td>2035</td>
<td>0</td>
<td>100</td>
<td>270</td>
</tr>
<tr>
<td>2040 +</td>
<td>0</td>
<td>200</td>
<td>270</td>
</tr>
</tbody>
</table>

Lowering discount rates is a possible strategy to place more weight on lowering future GHG
emissions linked to the operation and maintenance of major infrastructure facilities at the project
planning stage. The hypothesis is that weighting GHG-related costs in project planning will
encourage rehabilitation strategies that will reduce energy use and GHG emissions in networks. The Treasury Board of Canada has recently recommended a discount rate of approximately 8% (TBS 2007). In the United Kingdom, Stern et al. (2006) advocate the use of a 1.4% discount rate to reduce the risk of future climate damages. The use of a zero discount rate has also been suggested by Hasselmann et al. (1997) and Fearnside (2002) to calculate the net present value of climate change costs. This research will examine the impact of discount rates proposed in the literature on the replacement and rehabilitation decisions taken in the optimization of a Canadian water distribution network.

6.3 Review of Previous Research in Network Rehabilitation and Sustainable Network Design

For over 30 years, the water distribution system rehabilitation problem has been an active area of research. Shamir and Howard (1979) and Walski and Pelliccia (1982) were the first to propose a time-exponential model to forecast pipe break rates. Arulraj and Suresh (1995) developed a significance index to assess the improvement in nodal pressures that result from rehabilitating critical pipes in a network. Dandy and Engelhardt (2001) demonstrated the ability of genetic algorithms (GA) to optimize the scheduling of pipe replacement in a network. A GA was applied to the Adelaide water distribution system to minimize the cost of the project. Dandy and Engelhardt (2001) showed that the GA was able to identify the pipes to be replaced while considering an available budget constraint in the decision-making process. Dandy and Engelhardt (2006) proposed a multi-objective framework to minimize the rehabilitation costs and maximize network reliability simultaneously. The study accounted for the present value of rehabilitation costs and reliability as measured with the expected number of customer interruptions per year. A number of other studies have considered pipe rehabilitation in tandem with asset management
strategies. These studies are not reviewed here since the focus of the current research is on network rehabilitation and not on asset management strategies.

Only very recently have environmental considerations been included in the network design and expansion problem. Filion et al. (2004) were the first to develop a decision support system to determine the timing of water main replacement based on life-cycle energy considerations in the fabrication, use, and disposal stages of a network. Filion et al. (2004) assumed a single water main replacement schedule for all pipes; in practice, individual pipes or groups of pipes have different replacement schedules. Dandy et al. (2006 and 2008) were the first to develop a multi-objective optimization algorithm that incorporates objectives of whole-of-life-cycle costs, energy use, GHG emissions, and resource consumption. The optimization algorithm was applied to a real, complex network in Australia. Wu et al. (2008, 2010) used a multi-objective genetic algorithm (MOGA) to design a small, hypothetical water distribution network by minimizing its total present value cost and the mass of GHG emissions. Roshani and Filion (2009) developed a multi-objective optimization framework to optimize the pump and reservoir operations of a water transmission system to minimize construction, pumping energy, and GHG costs. Roshani et al. (2012) examined the influence of possible carbon mitigating policies (e.g., through a carbon tax and discounting) on the single-objective expansion of the moderately complex Fairfield water distribution system in Ontario, Canada. Their results indicated that carbon mitigating policies had no significant impact on energy use and GHG emissions in the design of the Fairfield system.

Previous studies have incorporated environmental objectives in the water distribution system design and expansion problem mainly to understand the effect of carbon mitigating strategies on design and expansion decisions and on energy use and GHG emissions in networks (Dandy et al. 2006 and 2008; Roshani and Filion 2009, 2012; Wu et al. 2008, 2010). Hypothetical, simplified networks have been used in most of these studies. The research results generated with these
simple networks are not directly transferable to real, complex networks and this is an important limitation of the previous research. To the authors’ knowledge, no approach to date has been proposed to examine the impact of carbon mitigating strategies on the optimization of the timing and type of water main rehabilitation in water distribution networks. This is owing to the complexity of solving the optimal water main rehabilitation timing problem which typically comprises a vast number of time-dependent rehabilitation and replacement decisions and requires a great deal of computational resources to solve.

In this research, the event-based rehabilitation timing optimization approach of Roshani and Filion (2012) is adapted and used to examine the impact of a carbon tax and of lowering discount rates on water main rehabilitation planning of a moderately complex water distribution network in Eastern Ontario, Canada. The new approach is also used to examine the impact of a carbon tax and of lowering discount rates on the energy use and GHG emissions in the rehabilitated network. The new algorithm includes leakage, pipe-break, and pipe-aging forecasting modules to appropriately capture the cost, energy use, and GHG emissions linked to leakage, pipe breaks, and increase in wall roughness in aging water mains.

The research makes two novel research contributions to the field of water distribution system research. First, it presents a novel water main rehabilitation timing optimization approach that accounts for energy use and GHG emissions linked to pumping electricity, leakage, and increases in pipe wall roughness due to pipe aging. Second, it is the first study to examine the impact of carbon mitigating strategies (e.g., carbon tax, and low discount rates) on water distribution network rehabilitation decisions in a real-world, complex system.

The chapter is organized as follows; the water main rehabilitation timing optimization problem is formulated with the inclusion of a carbon tax and discounting strategies. The pipe aging, pipe
leakage, and pipe break forecasting models integrated into the optimization approach are presented. The new water main rehabilitation optimization approach is applied to the Fairfield water distribution system in Amherstview, Ontario, Canada, under different carbon mitigating scenarios. The results from the scenario analysis and the sensitivity analysis performed on uncertain input parameters in the case study are discussed.

6.4 Problem Definition

The optimization approach developed in this research aims to find the optimal timing and type of water main rehabilitation that minimize the costs associated with capital infrastructure investments and continuing operational activities. Capital infrastructure investments include pipe replacement, pipe duplication, pipe cleaning and lining, and installing new pipes in future growth area(s). Continuing operational activities and costs include break repair costs, the cost of lost water to leakage, electricity costs of pumping and the cost associated with levying a carbon tax on the electricity used to pump water. The decision variables are the time, the type, and the place of pipe rehabilitation to undertake in a water distribution network. Possible types of rehabilitation interventions include pipe replacement (diameter), pipe duplication (diameter), installation of new pipe in area(s) slated for future growth (diameter), and the type of lining technology used (e.g., cement-mortar lining).

The novel gene-coding approach in the event-based rehabilitation optimization algorithm of Roshani and Filion (2012) was adopted here. (The reader can refer to Roshani and Filion (2012) for details.) A fast-elitist non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2002) was used to search the large decision space efficiently and minimize the following two objectives:
\begin{align}
\text{Obj1} &= \text{Min}(CC) = PV \left[ \sum_{t=0}^{T} \sum_{p=1}^{np} \left( RC_{t,p} + DC_{t,p} + LC_{t,p} + NP_{t,p} \right) \right]_{DR} \\
\text{Obj2} &= \text{Min}(OC) = PV \left[ \sum_{t=0}^{T} \sum_{p=1}^{np} \left( LkC_{t,p} + BC_{t,p} \right) + \sum_{t=0}^{T} \left( EC_{t} + GHGC_{t} \right) \right]_{DR} 
\end{align}

where \( CC \) = capital cost, \( OC \) = operational cost, \( t \) = time (in years), \( T \) = rehabilitation planning horizon of the project, \( PV \) = present value of the costs, \( DR \) = discount rate, \( p \) = pipe number, \( np \) = maximum pipe number, \( RC_{t,p} \) = replacement cost for \( p^{th} \) pipe in \( t^{th} \) year, \( DC_{t,p} \) = pipe duplication cost, \( LC_{t} \) = lining cost, \( NP_{t,p} \) = new pipe cost, \( LkC_{t,p} \) = cost of lost water, \( BC_{t,p} \) = break repair cost, \( EC_{t,p} \) = electricity cost, and \( GHGC_{t} \) = carbon cost associated with electricity use. Nodal continuity and loop energy conservation constraints are satisfied externally with EPANET2 (Rossman 2000). Additional constraints on maximum fluid velocity, minimum pipe pressure, and commercially-available pipe diameter have been included in the framework.

Pipe leakage, pipe break, and pipe wall roughness forecasting models were integrated into the optimization algorithm to evaluate changes in system performance linked to water main rehabilitation events.

6.4.1 Leak Forecasting Model

The pipe leakage forecasting model of Germanopoulos (1985) (later adapted by Alvisi et al. (2009)) was selected for its simplicity and its accuracy in estimating lost water and for its parsimonious data requirements. In this model, the percent of pipe wall surface area subject to leakage \( (\Omega) \) is a function of pipe diameter \( (d_{p}) \), pipe length \( (l_{p}) \) and pipe age \( (t) \) as well as two empirical parameters \( \beta \) and \( \nu \) as in (3)

\[ \Omega = \pi d_{p} l_{p} \nu \omega^{\beta} \]  

(3)
Both empirical variables were found to be $u = 4 \times 10^{-7}$ and $\beta = 0.13$ with water loss measurements over the period 1998-2003 (Thompson 2011).

### 6.4.2 Break Forecasting Model

The time-exponential break forecasting model of Shamir and Howard (1979) was used because the available break data were limited to break location and time, pipe material, pipe diameter, and pipe age and this limited data set did not warrant the use of a more complex model. The time-exponential model assumes that number of breaks ($Nbr$) is a function of pipe age ($t$), an initial break rate ($\alpha_0$), and a break growth rate ($\beta$) as in (4)

$$Nbr = \alpha_0 e^{\beta t}$$

Table 6-2 Pipe break data (number and pipe age at time of break) and calibrated and assumed parameters for the time-exponential pipe break forecasting model for the four pipe materials in the Fairfield network.

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>No. Breaks</th>
<th>Pipe Age at Time of Break (years)</th>
<th>Break Exponential Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>Avg.</td>
</tr>
<tr>
<td>DI</td>
<td>21</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>CI</td>
<td>65</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>PVC</td>
<td>6</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>AC</td>
<td>2</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>94</strong></td>
<td><strong>3</strong></td>
<td><strong>32</strong></td>
</tr>
</tbody>
</table>

Table 6-2 indicates the calibrated values of $\alpha_0$ and $\beta$ for cast iron (CI) and ductile iron (DI) pipe based on break data spanning the period 1982-2011 in Fairfield. Data for asbestos cement (AC) and polyvinyl chloride (PVC) pipes were scarce and so values of $\alpha_0$ and $\beta$ reported in the
literature were used (Shamir and Howard 1979; Walski and Pelliccia 1982; Kleiner and Rajani 1999; Mailhot et al. 2003).

6.4.3 Pipe Roughness Growth Forecasting Model
The roughness growth forecasting model of Sharp and Walski (1988) was used to forecast ‘C’ factors of CI and DI pipes. This model was selected because it is unique and no other models are currently available in the literature. Average Hazen-Williams ‘C’ factor values of 55 for CI pipe, 120 for concrete pipe, 120 for DI pipe and 150 for PVC pipes were found with flow test data (CH2MHiIl 2007). Since the roughness growth model only applies to ferrous pipes, the Hazen-Williams ‘C’ factors of PVC and AC pipe were held constant over the planning period. Holding the ‘C’ factor constant is expected to produce lower frictional energy losses and underestimate energy use and GHG emissions in a network. The impact of the Hazen-Williams ‘C’ factor on energy use and GHG emissions was examined in the sensitivity analysis presented later in the paper.

6.4.4 Model Implementation
Figure 6.1 indicates a flowchart of the OptiNET water main rehabilitation optimization model. OptiNET combines the NSGA-II algorithm of Deb et al. (2002) with the leak, break, and pipe roughness forecasting models described above and the EPANET2 network solver. First, an initial, random population of solutions is generated. The population of solutions is sent to the network model, pipe roughness, leakage, and pipe break forecasting models for hydraulic, economic, and environmental evaluation. In each year, the pipe rehabilitation interventions are applied to the network layout. Pipe roughness and leakage are updated with the forecasting models. The EPANET2 solver is then run to determine pressures and flows for the established pipe layout and pipe conditions. The energy use and GHG emissions linked to electricity use are calculated based
on the results of a 24-h extended period simulation (the complete set of simulations performed with EPANET2 are discussed in the next section).

Figure 6.1 Flow chart of OptiNET water main rehabilitation timing optimization model.
The break repair cost is estimated for the current year with the break forecasting model. The objective functions (1)-(2) are updated and errors are calculated for the current year. The hydraulic, economic, and environmental evaluations are repeated for all n years. The objective functions and cumulative errors (computed over n years) are used to perform crossover, mutation, and selection operations to select the next population of solutions. Successive populations are generated and evaluated until a stopping criterion is satisfied.

Figure 6.2 Schematic of Fairfield water distribution system.

6.5 Fairfield Water Distribution Network

The Fairfield system provides water service to the towns of Amherstview and Odessa with a population of 15,000 people. A schematic of the Fairfield system is shown in Figure 6.2. Table 6-3 indicates the length and age of pipes in the system. The old, eastern part of the system is dominated by CI and DI pipes, and the newer, western part of the system is dominated by PVC, DI, and concrete pipes. PVC pipes were used to replace old pipes and duplicate pipes (Thompson
2011). The unit price of PVC pipe obtained from a Canadian pipe distributor is indicated in Table 6-4. Pipe cleaning and cement-mortar lining costs from Walski (1986) in Table 6-4 were inflated to 2010 dollars (start of planning period).

Table 6-3 Pipe material, length, and age in the Fairfield system.

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Length (m)</th>
<th>Percent of Total Length</th>
<th>Median Pipe Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete (C)</td>
<td>1,342</td>
<td>3.2</td>
<td>1993</td>
</tr>
<tr>
<td>Cast Iron (CI)</td>
<td>10,959</td>
<td>26.4</td>
<td>1965</td>
</tr>
<tr>
<td>Mortar Lined Ductile Iron (DI)</td>
<td>13,388</td>
<td>32.4</td>
<td>1985</td>
</tr>
<tr>
<td>Polyvinyl Chloride (PVC)</td>
<td>15,774</td>
<td>38</td>
<td>1999</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>41,464</strong></td>
<td><strong>100</strong></td>
<td><strong>1985</strong></td>
</tr>
</tbody>
</table>

Table 6-4 Unit costs of commercially-available PVC pipes and DI pipes cleaning and lining costs (from Walski 1986).

<table>
<thead>
<tr>
<th>Nominal Diameter of PVC Pipe (mm)</th>
<th>Inside Diameter of PVC Pipe (mm)</th>
<th>Unit Price of PVC Pipe ($/m)</th>
<th>Pipe Cleaning and Lining Cost ($/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>160</td>
<td>29</td>
<td>63</td>
</tr>
<tr>
<td>200</td>
<td>210</td>
<td>48</td>
<td>63</td>
</tr>
<tr>
<td>250</td>
<td>258</td>
<td>72</td>
<td>68</td>
</tr>
<tr>
<td>300</td>
<td>307</td>
<td>97</td>
<td>68</td>
</tr>
<tr>
<td>350</td>
<td>356</td>
<td>103</td>
<td>68</td>
</tr>
<tr>
<td>400</td>
<td>404</td>
<td>134</td>
<td>68</td>
</tr>
<tr>
<td>450</td>
<td>453</td>
<td>169</td>
<td>N/A</td>
</tr>
<tr>
<td>500</td>
<td>502</td>
<td>210</td>
<td>N/A</td>
</tr>
<tr>
<td>600</td>
<td>600</td>
<td>304</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The planning period in the Fairfield system spans the period 2010-2030. In the Year 2010, the average day demand is 32 L/s in the Fairfield network. The average day demand is projected to
increase to 70.6 L/s in 2030 in Table 6-5 (CH2MHill 2007). A network expansion in the western part of Fairfield (expansion area #1 in Figure 6.2) will be completed in Year 10. A second expansion in the northern part of Fairfield will be completed in Year 20 (expansion area #2 in Figure 6.2). Extended period simulation (EPS) and the diurnal pattern reported in Roshani et. al (2012) were used to simulate average day demands over a typical 24-hour period in each year of the planning period. Nodal pressures and pipe velocities were checked under maximum hour demand conditions in Years 1, 10, and 20. Pressures and pipe velocities were checked under maximum day demand + fire conditions at critical junctions J-514 and J-551 (Figure 6.2) in Years 1, 10, and 20. A needed fire flow of 33 L/s was adopted in accordance with Fire Underwriters Survey (FUS) guidelines (FUS 1999). The hydraulic performance of the Fairfield system was characterized with a total of 20 extended period simulations, 3 maximum hour demand simulations, and 6 maximum day demand + fire flow simulations.

Table 6-5 Projected annual demand growth rates and current and projected water demands in the Town of Amherstview (from CH2MHill 2007).

<table>
<thead>
<tr>
<th>Water Use</th>
<th>Land Use (%)</th>
<th>Annual Growth Rate (%)</th>
<th>2010 Present Water Demand (L/s)</th>
<th>2030 Projected Water Demand (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>68</td>
<td>3.5</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Multi-residential</td>
<td>18</td>
<td>3.5</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Commercial</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Institutional</td>
<td>8</td>
<td>2</td>
<td>2</td>
<td>3.7</td>
</tr>
<tr>
<td>Industrial</td>
<td>10</td>
<td>1</td>
<td>3</td>
<td>4.1</td>
</tr>
<tr>
<td>New Industrial</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>8.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td></td>
<td><strong>32</strong></td>
<td><strong>70.6</strong></td>
</tr>
</tbody>
</table>
To characterize energy use over the planning period (20 years), annual energy use was calculated in each year by entering the average day diurnal pattern from Roshani et al. (2012) into EPANET2 to simulate the pumping head and discharge over a 24-h period. Heads and discharges were entered into the brake horsepower equation to calculate daily energy use and then multiplied by 365 days to estimate annual energy use. This procedure was repeated for each year and the total energy use over the 20-year planning period was calculated by summing annual energy use. The annual energy use was multiplied by the average price of electricity of 8¢/kWh (OEB 2012) to calculate the annual energy cost. The electricity price was assumed constant in the absence of reliable electricity price forecasting data.

The mass of GHG emissions linked to pumping operations was calculated using projections of Canada’s future energy fuel mix and GHG emission intensity factors (EIFs) produced by National Energy Board (NEB 2007) and S & T Consultants Inc. (2008). The projected average emission intensity factors for Canada were applied to the Eastern Ontario region since the Ontario and average Canadian fuel mixes are similar (Environment Canada 2009). The full details of the energy fuel mix and emission intensity factor analysis are presented in Roshani et al. (2012). The GHG costs in (2) were calculated by multiplying the mass of GHG emissions in a particular year by the appropriate carbon tax level for that year (Table 6-1). Note that the carbon tax values in Table 6-1 for the years 2035 and 2040 were not used in the analysis since the planning period spans the Years 2010-2030.

6.6 Results and Discussions

Six carbon mitigating scenarios were examined in this study. Scenario 1 (Scn. 1) is the “No Tax” (NT) scenario where no carbon tax is levied and the discount rate stands at the current level of 8% for public infrastructure projects in Canada (TBS 2007). In Scenario 2 (Scn. 2), no carbon tax is
levied and the discount rate is lowered to 1.4%, as suggested by Stern et al. (2006). In Scenario 3 (Scn. 3), the NRTEE “Slow and Shallow” (SS) carbon tax trajectory is applied and the discount rate is set to 8%. In Scenario 4 (Scn. 4), the NRTEE “Slow and Shallow” (SS) carbon tax trajectory is again applied and the discount rate is set to 1.4%. In Scenario 5 (Scn. 5), the NRTEE “Fast and Deep” (FD) carbon tax trajectory is applied and the discount rate is set to 8%. In Scenario 6 (Scn. 6), the NRTEE “Fast and Deep” (FD) carbon tax trajectory is applied and the discount rate is set to 1.4%. In this study, capital costs, operating costs, and GHG costs are discounted using the same constant discount rate.

6.6.1 Effect of Discount Rate and Carbon Tax on the Location of Pareto Fronts

The optimization algorithm was run for Scenarios 1 through 6 and the Pareto fronts generated in each scenario are indicated in Figure 6.3. The discount rate applied in each scenario has a large impact on the location of the Pareto fronts in Figure 6.3. Scenarios 1, 3, and 5 with a high discount rate of 8% have Pareto fronts in the lower-left area of Figure 6.3. This is because a small weight is placed on future capital and operational costs which reduces the cost components in the objectives functions (1)-(2). Conversely, Scenarios 2, 4, and 6 with a low discount rate of 1.4% have Pareto fronts in the upper-right area of Figure 6.3 since a greater weighting is placed on future costs. The discount rate also has an impact on the shape (width and the height) of the Pareto fronts. In Scenarios 2, 4, and 6 with a low discount rate of 1.4%, the width of the Pareto fronts sits at approximately $3.0 M while in Scenarios 1, 3, and 5 (discount rate of 8%), the front width sits at approximately $2 M. This is an artifact of compound discounting where a lower discount rate tends to increase the sensitivity of present value costs to changes in future costs.
The results in Figure 6.3 suggest that the carbon tax has a small impact on costs and the location of Pareto fronts. When the discount rate is set to 8%, the FD carbon tax trajectory in Scenario 5 (Scn. 5) lowers the operational costs and the Pareto front of this scenario dominates all others. This is owing to the fact that the higher carbon tax level place a higher weighting on electricity costs tied to leakage and frictional energy losses in old deteriorated pipes which encourages the search process to invest in early pipe rehabilitation to reduce subsequent energy requirements and costs. When the discount rate is set to 1.4%, the impact of the FD carbon tax trajectory is much less significant. This is evident in Figure 6.3 where the Pareto front of Scenario 6 (CT=FD, DR=1.4%) overlaps almost perfectly with the Scenario 2 front (CT=NT, DR=1.4%). The lower discount rate of 1.4% places a heavy weighting on future energy-related costs (leakage, frictional
losses) and thus encourages the search process to invest heavily and early in pipe rehabilitation and replacement in both Scenarios 2 and 6. The weighting effect of the discount rate outstrips that of the carbon tax and thus reduces the influence of the FD trajectory in forcing the search process to adopt early replacement and rehabilitation. Interestingly, the Scenario 4 front (CT=SS, DR=1.4%) is dominated by the Scenario 2 front (CT=NT, DR=1.4%) where no carbon tax is applied. It is possible that in the SS trajectory of Scenario 4, the carbon tax is not increased fast enough to place a large enough weight on future costs. As a result, the search process fails to invest early in rehabilitation to decrease future costs in any significant way.

In the sections that follow, the energy use, GHG emissions, and costs will be compared between solutions located at opposite ends of the Pareto fronts in Figure 6.3. In this figure, select solutions in distinct regions of each Pareto front are indicated with a circle. These solutions are the minimum capital cost solutions (left side of fronts), the minimum operational cost solutions (right side of fronts), and the minimum total cost solutions (at or near the elbow of the fronts). In Table 6-6 through Table 6-8, the minimum capital cost solution is identified with the hyphenated identifier “-1” (e.g., Scn. 1-1), the minimum operational cost solution is identified with “-2” (e.g., Scn. 1-2), and the minimum total cost solution is identified with “-3” (e.g., Scn. 1-3).

**6.6.2 Effect of Discount Rate and Carbon Tax on Energy Use and GHGs**

Discount rate was found to have a small influence on energy use and GHG emissions generated in the Fairfield distribution network. At different carbon tax levels, lowering the discount rate from 8% to 1.4% was found to decrease GHGs from 0.3-7.6% in the minimum total cost solutions (“-3”) of Table 6-6. (It is noted that lowering the discount rate from 8% to 1.4% under the SS carbon tax trajectory resulted in a 0.9% increase in GHGs.) These results are explained by a lower discount rate that places more weight on future costs and encourages the search process to invest
in rehabilitation in the opening years to lower the continuing costs linked to leakage and break repairs that dominate (2). In the process of reducing lost water and repair costs, the search process also reduces energy and GHG costs and emissions (albeit by smaller amounts) even though these last two costs only account for a small portion of the operational cost in (2).

Applying a carbon tax on electricity was found to produce modest increases and decreases in GHG emissions across minimum total cost solutions (“-3”) in Scenarios 1 through 6. At a discount rate of 8% in Table 6-6, moving from a NT to a SS tax trajectory produced a 3.3% increase in GHG emissions while moving from a SS to a FD trajectory produced a 1.3% increase in GHG emissions. At a discount rate of 1.4%, moving from a NT to a SS trajectory resulted in a slight increase of 4.6% in GHG emissions, while a move from a SS to a FD trajectory resulted in a decrease of 9.6% GHG emissions. The small sensitivity of GHG emissions to an increase in carbon tax is owing to the fact that the energy and GHG costs account for a small portion of the annual operational cost (approximately 6~8%) relative to the lost water and repair costs in (2). Most of the energy to pump water is used to satisfy the static head of 48 m in the system which is unaffected by pipe rehabilitation.
Table 6-6 Average annual costs, annual greenhouse gas emissions, present value capital costs, present value operational costs, and present value total costs for select solutions generated in Scenarios 1 through 6.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Tax Scn. (4)</th>
<th>DR (%)</th>
<th>Break</th>
<th>Leak</th>
<th>Energy</th>
<th>Cap. Cost</th>
<th>Opr. Cost</th>
<th>Total Cost</th>
<th>GHG-e (tonne)</th>
<th>PV Cap. Cost ($M)</th>
<th>PV Opr. Cost ($M)</th>
<th>PV Total Cost ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scn. 1-1(1)</td>
<td>NT 8</td>
<td></td>
<td>48.4</td>
<td>282.7</td>
<td>42.8</td>
<td>334.2</td>
<td>373.9</td>
<td>708.1</td>
<td>0</td>
<td>90.5</td>
<td>3.7</td>
<td>3.6</td>
</tr>
<tr>
<td>Scn. 1-2(2)</td>
<td>NT 8</td>
<td></td>
<td>18.1</td>
<td>110.8</td>
<td>39.4</td>
<td>491.8</td>
<td>168.2</td>
<td>660</td>
<td>0</td>
<td>83.9</td>
<td>5.5</td>
<td>2</td>
</tr>
<tr>
<td>Scn. 1-3(3)</td>
<td>NT 8</td>
<td></td>
<td>28.1</td>
<td>166</td>
<td>41.4</td>
<td>361.7</td>
<td>235.5</td>
<td>597.1</td>
<td>0</td>
<td>88</td>
<td>4</td>
<td>2.4</td>
</tr>
<tr>
<td>Scn. 2-1</td>
<td>NT 1.4</td>
<td></td>
<td>49</td>
<td>259.8</td>
<td>43.9</td>
<td>313.6</td>
<td>352.7</td>
<td>666.3</td>
<td>0</td>
<td>93.4</td>
<td>5.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Scn. 2-2</td>
<td>NT 1.4</td>
<td></td>
<td>18.2</td>
<td>99.3</td>
<td>40.8</td>
<td>518.1</td>
<td>158.3</td>
<td>676.5</td>
<td>0</td>
<td>86.9</td>
<td>9</td>
<td>2.9</td>
</tr>
<tr>
<td>Scn. 2-3</td>
<td>NT 1.4</td>
<td></td>
<td>22.6</td>
<td>131.1</td>
<td>41.2</td>
<td>359.4</td>
<td>194.9</td>
<td>554.2</td>
<td>0</td>
<td>87.7</td>
<td>6.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Scn. 3-1</td>
<td>NT 8</td>
<td></td>
<td>56.6</td>
<td>284</td>
<td>43.9</td>
<td>333.5</td>
<td>387.5</td>
<td>721</td>
<td>2.9</td>
<td>93</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Scn. 3-2</td>
<td>SS 8</td>
<td></td>
<td>37.9</td>
<td>166.4</td>
<td>41.7</td>
<td>562.9</td>
<td>248.8</td>
<td>811.7</td>
<td>2.8</td>
<td>88.5</td>
<td>5.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Scn. 3-3</td>
<td>SS 1.4</td>
<td></td>
<td>43.5</td>
<td>231.2</td>
<td>42.9</td>
<td>338.7</td>
<td>320.5</td>
<td>659.2</td>
<td>2.8</td>
<td>90.9</td>
<td>3.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Scn. 4-1</td>
<td>SS 1.4</td>
<td></td>
<td>55.4</td>
<td>319.8</td>
<td>46.5</td>
<td>338.9</td>
<td>424.7</td>
<td>763.6</td>
<td>3.1</td>
<td>98.6</td>
<td>6</td>
<td>7.3</td>
</tr>
<tr>
<td>Scn. 4-2</td>
<td>SS 1.4</td>
<td></td>
<td>21.8</td>
<td>120.8</td>
<td>41.9</td>
<td>497.5</td>
<td>187.1</td>
<td>684.7</td>
<td>2.7</td>
<td>89.4</td>
<td>8.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Scn. 4-3</td>
<td>SS 1.4</td>
<td></td>
<td>28.9</td>
<td>165.8</td>
<td>43.1</td>
<td>362.7</td>
<td>240.7</td>
<td>603.4</td>
<td>2.8</td>
<td>91.7</td>
<td>6.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Scn. 5-1</td>
<td>FD 8</td>
<td></td>
<td>45.9</td>
<td>302.2</td>
<td>43.2</td>
<td>301</td>
<td>398.8</td>
<td>699.7</td>
<td>7.5</td>
<td>91.2</td>
<td>3.3</td>
<td>3.7</td>
</tr>
<tr>
<td>Scn. 5-2</td>
<td>FD 8</td>
<td></td>
<td>18.8</td>
<td>99.7</td>
<td>38.4</td>
<td>490.7</td>
<td>163.3</td>
<td>654.1</td>
<td>6.5</td>
<td>81.4</td>
<td>5.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Scn. 5-3</td>
<td>FD 8</td>
<td></td>
<td>20.1</td>
<td>134.9</td>
<td>42.2</td>
<td>368.6</td>
<td>203.8</td>
<td>572.4</td>
<td>7</td>
<td>89.7</td>
<td>4.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Scn. 6-1</td>
<td>FD 1.4</td>
<td></td>
<td>34.8</td>
<td>213.4</td>
<td>44.1</td>
<td>318.4</td>
<td>299.5</td>
<td>617.9</td>
<td>7.3</td>
<td>93.7</td>
<td>5.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Scn. 6-2</td>
<td>FD 1.4</td>
<td></td>
<td>17.7</td>
<td>88.6</td>
<td>38.9</td>
<td>448.4</td>
<td>152</td>
<td>600.4</td>
<td>6.7</td>
<td>82.1</td>
<td>7.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Scn. 6-3</td>
<td>FD 1.4</td>
<td></td>
<td>20.8</td>
<td>117.2</td>
<td>39.3</td>
<td>379.8</td>
<td>184.1</td>
<td>563.9</td>
<td>6.8</td>
<td>82.9</td>
<td>6.6</td>
<td>3.3</td>
</tr>
</tbody>
</table>

(1) The “-1” identifier denotes the minimum capital cost solution.
(2) The “-2” identifier denotes the minimum operational cost solution.
(3) The “-3” identifier denotes the minimum total cost solution.
(5) Million dollars.
Table 6-7 Main length rehabilitated, age of rehabilitation, and percent of mains rehabilitated for select solutions in Scenarios 1 through 6.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Tax Scn. (2)</th>
<th>DR (%)</th>
<th>Length (m)</th>
<th>Avg. Age (Year)</th>
<th>Percent of Total Length (%)</th>
<th>Length (m)</th>
<th>Avg. Age (Year)</th>
<th>Percent of Total Length (%)</th>
<th>Length (m)</th>
<th>Avg. Age (Year)</th>
<th>Percent of Total Length (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scn. 1(1)</td>
<td>NT</td>
<td>8</td>
<td>47,397</td>
<td>31.3</td>
<td>66.1</td>
<td>10,914</td>
<td>30.1</td>
<td>15.2</td>
<td>13,438</td>
<td>29.9</td>
<td>18.7</td>
</tr>
<tr>
<td>Scn. 2</td>
<td>NT</td>
<td>1.4</td>
<td>47,726</td>
<td>32.5</td>
<td>64.9</td>
<td>11,148</td>
<td>32</td>
<td>15.2</td>
<td>14,622</td>
<td>30.4</td>
<td>19.9</td>
</tr>
<tr>
<td>Scn. 3</td>
<td>SS</td>
<td>8</td>
<td>43,577</td>
<td>30.9</td>
<td>64.6</td>
<td>12,078</td>
<td>32.3</td>
<td>17.9</td>
<td>11,824</td>
<td>28.2</td>
<td>17.5</td>
</tr>
<tr>
<td>Scn. 4</td>
<td>SS</td>
<td>1.4</td>
<td>46,177</td>
<td>31.4</td>
<td>63</td>
<td>12,972</td>
<td>29.3</td>
<td>17.7</td>
<td>14,131</td>
<td>27.8</td>
<td>19.3</td>
</tr>
<tr>
<td>Scn. 5</td>
<td>FD</td>
<td>8</td>
<td>46,261</td>
<td>31.4</td>
<td>64.6</td>
<td>10,686</td>
<td>29.4</td>
<td>14.9</td>
<td>14,700</td>
<td>29</td>
<td>20.5</td>
</tr>
<tr>
<td>Scn. 6</td>
<td>FD</td>
<td>1.4</td>
<td>51,459</td>
<td>29.6</td>
<td>68.5</td>
<td>11,056</td>
<td>27.2</td>
<td>14.7</td>
<td>12,625</td>
<td>32.2</td>
<td>16.8</td>
</tr>
</tbody>
</table>

(1) The minimum total cost solution was selected for each scenario.
(2) NT: No Tax, SS: Slow and Shallow, FD: Fast and Deep.
Table 6-8 The length and percent of mains rehabilitated over the planning period for select solutions in Scenarios 1 through 6.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total Length (m)</th>
<th>Replaced (m) (%)</th>
<th>Duplicated (m) (%)</th>
<th>Relined (m) (%)</th>
<th>Total (m) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1-6</td>
<td>7-13</td>
<td>14-20</td>
<td>1-6</td>
</tr>
<tr>
<td>Scn. 1</td>
<td>71,749</td>
<td>19,672 (27)</td>
<td>6,812 (9)</td>
<td>20,913 (29)</td>
<td>4,672 (7)</td>
</tr>
<tr>
<td>Scn. 2</td>
<td>73,496</td>
<td>17,851 (24)</td>
<td>7,829 (11)</td>
<td>22,046 (30)</td>
<td>4,113 (6)</td>
</tr>
<tr>
<td>Scn. 3</td>
<td>67,479</td>
<td>19,710 (29)</td>
<td>5,934 (9)</td>
<td>17,933 (27)</td>
<td>1,325 (2)</td>
</tr>
<tr>
<td>Scn. 4</td>
<td>73,280</td>
<td>20,328 (28)</td>
<td>5,501 (8)</td>
<td>20,348 (28)</td>
<td>5,827 (8)</td>
</tr>
<tr>
<td>Scn. 5</td>
<td>71,648</td>
<td>18,751 (26)</td>
<td>7,778 (11)</td>
<td>19,732 (28)</td>
<td>4,902 (7)</td>
</tr>
<tr>
<td>Scn. 6</td>
<td>75,140</td>
<td>21,559 (29)</td>
<td>9,621 (13)</td>
<td>20,279 (27)</td>
<td>3,320 (4)</td>
</tr>
</tbody>
</table>

(1) The minimum total cost solution was selected for each scenario.

(2) The first number is the length of pipe rehabilitated and the number in parentheses is the percent of the total length of pipe rehabilitated.
6.6.3 Effect of Discount Rate and Carbon Tax on Water Loss and Break Repair Cost

The results in Table 6-6 suggest that lowering the discount rate significantly reduces pipe break repair costs and leakage costs across minimum total cost solutions (“-3”) in Scenarios 1 through 6. At different carbon tax levels, reducing the discount rate from 8% to 1.4% reduces the annual break repair costs by 19.6-33.6%, and annual leakage costs by 12.9-28.3%. (It is noted that for the FD trajectory, lowering the discount rate from 8% to 1.4% results in a 4% increase in annual repair cost.) Lowering the discount rate places more weight on continuing leakage and pipe break repair costs. This increased weighting in turn encourages the search process to find solutions that invest heavily and early in pipe rehabilitation to reduce annual leakage and repair costs incurred in the middle and end of the planning period.

Table 6-6 suggests that carbon tax can also have a significant impact on annual pipe break repair cost and leakage cost across minimum total cost solutions (“-3”) in Scenarios 1 through 6. Increasing the carbon tax from NT to SS significantly increased annual break repair cost by 27.9-54.8% (for 1.4% and 8% rates) and annual leakage cost by 26.5-39.2% (for 1.4% and 8% rates). This is because the SS tax trajectory produces only small GHG costs in the optimization and fails to forcefully steer the search process to rehabilitate pipes early in the planning period. Conversely, increasing the carbon tax further from SS to FD significantly decreased annual break repair cost by 28.0-54.0% and leakage cost by 29.3-41.8% (for 1.4% and 8% rates). The FD tax trajectory (unlike its SS counterpart) is aggressive enough to drive the search process to rehabilitate pipe early in the planning period to significantly decrease pipe breaks and leakage in the system.

6.6.4 Effect of Discount Rate and Carbon Tax on Rehabilitation Decision Type and Timing

The impact of discount rate on the length of pipe replaced, pipe lined, and pipe duplicated was examined in Table 6-7. This table indicates the length, average age and percent of total length of
pipe replaced, pipe duplicated, and pipe relined for the minimum total cost solutions (“-3”) in Scenarios 1 through 6. Table 6-7 indicates that lowering the discount rate from 8% to 1.4% at all carbon tax levels leads to a modest 0.7-11.2% increase in pipe replacement length and a modest 2.1-7.4% increase in pipe duplication length. This is owing to a low discount rate that places a higher weight on future operational costs and thus encourages the search process to increase the length of pipes replaced and duplicated to lower costs linked to leakage and energy use. Further, lowering the discount rate from 8% to 1.4% under the NT and SS tax trajectories increases the length of lined pipe by 8.8-19.5%. However, lowering the discount rate from 8% to 1.4% under the FD tax trajectory decreases the length of lined pipe by 14.1%. Here, the FD trajectory imposes a higher weight on operational cost to encourage the search process to invest in pipe replacement and pipe duplication and reduce the length of lined pipe.

The impact of carbon tax on the length of pipe replaced, pipe lined, and pipe duplicated for minimum total cost solutions (“-3”) in Scenarios 1 through 6 was also examined in Table 6-7. Moving from a NT to a SS trajectory (at 8% and 1.4% rates) produced a small 3.2%-8.0% decrease in pipe replacement length, a modest 10.7%-16.4% increase in pipe duplication, and a modest 3.4%-12.0% decrease in pipe lining. Here, the decrease in pipe replacement is accompanied by an increase in pipe duplication to ensure an adequate level of hydraulic capacity and contain frictional losses in the network. Further, moving from a SS to a FD trajectory (at 8% and 1.4% rates) produced a modest 6.2%-11.4% increase in pipe replacement length, a modest 11.5-14.8% decrease in pipe duplication, and a significant 24.3% increase in lining (at an 8% rate) and a modest 10.6% decrease in lining (at an 1.4% rate). Since the FD trajectory imposes a large weight on future energy costs, it encourages the search process to select solutions which rely heavily on pipe replacement and pipe duplication to reduce leakage and frictional losses – two factors that affect energy use.
The impact of discount rate on the timing of pipe rehabilitation was also examined. Table 6-8 indicates the total length of pipe replaced, duplicated, and lined over three time intervals within the 20-year planning period (e.g., Years 1-6, Years 7-13, and Years 14-20) for the minimum total cost solutions (“-3”) in Scenarios 1 through 6. The results in Table 6-8 suggest that lowering discount rate from 8% to 1.4% tends to shift the rehabilitation activities to the first and second time intervals. This is because a low discount rate puts more weight on future operational costs and thereby encourages the search process to choose solutions that shift pipe replacement, duplication, and lining to the beginning and middle of the planning period to lower the present value of these costs.

The results in Table 6-8 also suggest that moving to a more aggressive carbon tax trajectory (from NT to FD) tends to shift rehabilitation activities to the first and second time intervals. The reason again is that a higher carbon tax places more weight on future energy use which in turn encourages the search process to seek out solutions that place their rehabilitation activities near the beginning of planning period to minimize the present value of carbon tax-related costs. This is corroborated by data in Table 6-7 that suggests that pipe age at the time of rehabilitation is lower in scenarios with a low discount rate and a carbon tax trajectory.

6.6.5 Differences in Leakage Costs, Pipe Break Repair Costs, and Energy Costs across Minimum Capital Cost Solutions and Minimum Operational Cost Solutions

The differences in leakage, pipe repair, and energy costs between the minimum capital cost solutions and minimum operational cost solutions in Scenarios 1 through 6 was also examined. The leakage cost was found to vary significantly between minimum capital cost solutions and minimum operational cost solutions since it accounts for the largest portion of the operational cost in the Fairfield system. The central and eastern parts of the Fairfield network are populated with old CI and DI water mains with high leakage levels. The high leakage level presents an
opportunity for the search process to significantly reduce the costs of leakage by investing heavily and early in pipe rehabilitation and replacement of old CI and DI pipes in these regions. Evidence of this is found in Table 6-6 where for all 6 scenarios, the leakage cost for minimum operational cost solutions (“-2”) is 41.4-67% lower than that of the minimum capital cost solutions (“-1”). Further evidence is found in Figure 6.4 which compares the annual leakage cost between the minimum capital cost solution of Scenario 6 (Scn. 6-1) and the minimum operational cost solution of Scenario 6 (Scn. 6-2) (where the FD tax and a discount rate of 1.4% are applied). At the beginning of the planning period, both solutions have approximately the same annual leakage cost. However, the minimum operational cost solution benefits from heavy and early investment in pipe rehabilitation which reduces the leakage through the end of the planning period. Conversely, in the minimum capital cost solution, the search process instead chooses to reduce pipe rehabilitation investments in the middle and near the end of the planning period which increases leakage and operational cost in the middle years to the end of the planning period.

![Figure 6.4 Time variation of annual cost of lost water for minimum capital cost solution (“-1”) and minimum operational cost solution (“-2”) of Scenario 6 (CT=FD, DR=1.4%).](image)

*Figure 6.4 Time variation of annual cost of lost water for minimum capital cost solution (“-1”) and minimum operational cost solution (“-2”) of Scenario 6 (CT=FD, DR=1.4%).*
Similarly, the pipe break repair cost was found to vary significantly between minimum capital cost solutions and minimum operational cost solutions. Table 6-6 shows that for all 6 scenarios, the pipe break cost for minimum operational cost solutions (“-2”) was 33.0-62.8% lower than that of the minimum capital cost solutions (“-1”). This is owing to the fact that in minimum operational cost solutions (“-2”), there is a heavy and early investment in pipe replacement and rehabilitation to lower continuing pipe repair costs.

The annual energy costs and annual GHG emissions of the minimum operational cost solutions were also found to be lower than that of the minimum capital cost solutions. Table 6-6 indicates that the annual energy costs of the minimum operational cost solutions (“-2”) were 5-11.8% lower than that of the minimum capital cost solutions (“-1”). Similarly, the annual GHG emissions of the minimum operational cost solutions (“-2”) were 4.8-12.4% lower than the minimum capital cost solutions (“-1”). This is again owing to the fact that minimum operational cost solutions (“-2”) benefit from heavy and early investment in pipe replacement and pipe rehabilitation. Newly replaced pipes have more capacity (e.g., higher Hazen-Williams ‘C’ factors) and reduce the frictional losses and the energy required to pump water through them. Newly replaced pipes also leak less which reduces the pumped volume and energy use and GHG emissions linked to pumping water.

6.7 Sensitivity Analysis

The previous scenario analysis indicated that the main drivers of cost and GHG emissions were water demand, leakage, and pipe breaks. A sensitivity analysis was performed to examine the impact of selected parameters (forecasted demand, initial leak rate, leak growth rate, initial break rate, break growth rate, and Hazen-Williams ‘C’ factor) on the objective function cost values and on GHG emissions. All sensitivity analysis runs were performed for Scenario 6 where a FD tax
trajectory and a discount rate of 1.4% were applied. A total of 8 sensitivity analysis runs were performed to examine: (1) a 15% increase in forecasted water demand, (2) a 15% decrease in forecasted water demand, (3) a 15% increase in initial leak rate, (4) a 15% decrease in initial leak rate, (5) a 15% increase in leak growth rate, (6) a 15% increase in initial break rate, (7) a 15% increase in break growth rate, and (8) a 15% decrease in Hazen-Williams ‘C’ factor as indicated in Table 6-9. The mean and standard deviations of costs were computed with the objective function values (and their cost components) for all the solutions on the Pareto front of the final generation.

6.7.1 Capital Costs
The results in Table 6-9 suggest that capital costs are moderately sensitive to uncertainties in forecasted demand and leakage growth. Table 6-9 indicates that a 15% increase in forecasted demand results in a 10.3% increase in the present value of capital cost. A 15% increase in forecasted demand results in a 9% increase in pipe replacement cost and a 19% increase in pipe duplication cost. These results suggest that an increase in demand encourages the search process to replace and duplicate pipes to increase the hydraulic capacity of the network. Further, a 15% decrease in forecasted water demand results in a 7.6% decrease in pipe replacement cost. Since pipe replacement accounts for a large portion of capital costs, a decrease in pipe replacement creates savings to undertake a 12.6% increase in pipe lining and an additional 28.3% increase in pipe duplication expenditures.

Similarly, a 15% increase in leakage growth results in a 10.3% increase in the present value of capital cost. The same increase in leakage growth rate results in a 5% increase in pipe replacement cost, a 35% increase in pipe duplication cost, and a 4% increase in pipe lining cost. To offset the higher leakage level, the search process replaces, lines, and duplicates old,
deteriorated pipes. Pipe duplication reduces pressures in the network and thereby decreases leakage. (It should be noted that part of this pipe duplication is to increase the system capacity to supply the lost water in the network).

### 6.7.2 Operational Costs

The results in Table 6-9 suggest that operational costs are moderately sensitive to uncertainties in forecasted demand and highly sensitive to leakage growth. Table 6-9 indicates that a 15% increase in forecasted demand results in a 21.4% increase in the present value of operational cost and that a 15% increase in leakage growth results in a 85.7% increase in the present value of operational cost. Not surprisingly, increases in forecasted water demand and leak growth rate produce corresponding increases in annual energy costs and annual lost water costs (see Table 6-9). Increasing the leakage growth rate by 15% also leads to a reduction of 21.2% in annual break repair cost. This is owing to a higher leak rate that drives the search process to choose solutions with more pipe replacement and pipe duplication which also reduces the number of pipe breaks in the system.
Table 6-9 Results of the sensitivity analysis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scenario</th>
<th>Sen.6 (CT=FD; DR=1.4%)</th>
<th>+15% Future</th>
<th>-15% Future</th>
<th>+15% Initial</th>
<th>-15% Initial</th>
<th>+15% Leak Growth Rate</th>
<th>-15% Leak Growth Rate</th>
<th>+15% Break Growth Rate</th>
<th>-15% Break Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost ($M)</td>
<td></td>
<td>6.8 (0.8)</td>
<td>7.5 (1.0)</td>
<td>6.8 (1.1)</td>
<td>7.0 (0.94)</td>
<td>6.9 (0.8)</td>
<td>7.5 (0.8)</td>
<td>6.9 (0.8)</td>
<td>6.8 (0.9)</td>
<td>6.7 (0.9)</td>
</tr>
<tr>
<td>Average Annual Pipe Replacement Cost ($1,000)</td>
<td></td>
<td>252.6 (41.3)</td>
<td>275.3 (44.4)</td>
<td>233.3 (45.5)</td>
<td>252.8 (43.2)</td>
<td>243.2 (41.2)</td>
<td>264.7 (38.0)</td>
<td>243.3 (36.9)</td>
<td>251.6 (37.3)</td>
<td>242.8 (45.2)</td>
</tr>
<tr>
<td>Average Annual Lining Cost ($1,000)</td>
<td></td>
<td>45.2 (6.2)</td>
<td>42.6 (6.1)</td>
<td>50.9 (8.7)</td>
<td>46.1 (7.2)</td>
<td>46.0 (6.9)</td>
<td>47.0 (6.9)</td>
<td>50.3 (7.3)</td>
<td>46.6 (7.1)</td>
<td>48.6 (7.7)</td>
</tr>
<tr>
<td>Average Annual Pipe Duplication Cost ($1,000)</td>
<td></td>
<td>61.9 (9.5)</td>
<td>73.7 (13.6)</td>
<td>79.4 (15.3)</td>
<td>65.8 (12.5)</td>
<td>74.2 (10.9)</td>
<td>83.5 (13.0)</td>
<td>71.8 (11.5)</td>
<td>63.2 (14.4)</td>
<td>67.1 (11.6)</td>
</tr>
<tr>
<td>Average Annual New Pipe Installation Cost ($1,000)</td>
<td></td>
<td>27.3 (3.4)</td>
<td>34.1 (3.7)</td>
<td>25.1 (3.3)</td>
<td>34.5 (5.4)</td>
<td>27.3 (4.0)</td>
<td>31.5 (3.3)</td>
<td>27.3 (4.6)</td>
<td>28.4 (4.4)</td>
<td>26.1 (3.8)</td>
</tr>
<tr>
<td>Operational Cost ($M)</td>
<td></td>
<td>4.2 (1.0)</td>
<td>5.1 (1.3)</td>
<td>5.0 (1.5)</td>
<td>4.9 (1.4)</td>
<td>4.1 (1.0)</td>
<td>7.8 (1.8)</td>
<td>4.5 (1.0)</td>
<td>4.9 (0.9)</td>
<td>4.5 (1.2)</td>
</tr>
<tr>
<td>Average Annual Lost Water Cost ($1,000)</td>
<td></td>
<td>160.1 (50.8)</td>
<td>196.0 (63.7)</td>
<td>199.4 (74.5)</td>
<td>201.3 (69.3)</td>
<td>154.0 (46.6)</td>
<td>366.5 (102.7)</td>
<td>172.4 (50.8)</td>
<td>159.9 (37.0)</td>
<td>176.3 (59.0)</td>
</tr>
<tr>
<td>Average Annual Energy Cost ($1,000)</td>
<td></td>
<td>41.2 (1.9)</td>
<td>49.6 (2)</td>
<td>41.7 (2.3)</td>
<td>42.8 (1.9)</td>
<td>42.1 (1.5)</td>
<td>47.7 (2.4)</td>
<td>41.9 (1.5)</td>
<td>41.7 (1.3)</td>
<td>41.9 (1.4)</td>
</tr>
<tr>
<td>Average Annual Break Repair Cost ($1,000)</td>
<td></td>
<td>29.7 (9.4)</td>
<td>36.1 (11.4)</td>
<td>36.3 (12.8)</td>
<td>31.1 (9.7)</td>
<td>31.3 (9.2)</td>
<td>23.4 (5.4)</td>
<td>35.3 (10.4)</td>
<td>69.8 (18.4)</td>
<td>31.8 (9.7)</td>
</tr>
<tr>
<td>Average Annual GHG Cost ($1,000)</td>
<td></td>
<td>6.9 (0.3)</td>
<td>8.1 (0.4)</td>
<td>6.7 (0.4)</td>
<td>7.1 (0.3)</td>
<td>7.0 (0.2)</td>
<td>7.5 (0.4)</td>
<td>7.0 (0.2)</td>
<td>7.0 (0.2)</td>
<td>7.0 (0.2)</td>
</tr>
<tr>
<td>Average Annual GHG Emissions (tonnes)</td>
<td></td>
<td>87.5 (4.2)</td>
<td>105.8 (4.1)</td>
<td>89.3 (5)</td>
<td>91.1 (4.2)</td>
<td>89.5 (3.2)</td>
<td>102.5 (5.0)</td>
<td>89.2 (3.4)</td>
<td>88.8 (2.9)</td>
<td>89.2 (3.1)</td>
</tr>
</tbody>
</table>

(1) Million dollars.
(2) The first number is the mean value and the second number is the standard deviation.
6.7.3 Greenhouse Gas Emissions
The results in Table 6-9 suggest that GHG emissions are moderately sensitive to water demand and leakage growth rate. Specifically, a 15% increase in forecasted water demand results in a 20.9% increase in annual GHG emissions and a 15% increase in leak growth rate results in a 17.1% increase in annual GHG emissions. Not surprisingly, an increase in water demand and leakage both increase the pumping and electricity requirements of the system and the GHGs associated with electricity production to operate the pumps.

6.8 Summary and Conclusions
A new multi-objective optimization approach was developed and used to solve the optimal pipe rehabilitation timing problem for six carbon mitigating scenarios. The optimization approach was applied to the real-world Fairfield water distribution network in eastern Ontario, Canada. The results suggested that adopting a low discount rate and levying a carbon tax had a small impact in reducing energy use and GHG emissions because these accounted for a small portion of the total operational costs. Further, a low discount rate and the application of a carbon tax had a significant impact in reducing leakage and pipe breaks and encouraged the search process to invest in rehabilitation early in the planning period to reduce the continuing costs of leakage, pipe repair, energy and GHG emissions. A sensitivity analysis suggested that water demand and leakage growth rate had a moderate to significant impact on the present value of capital and operational costs and on GHG emissions in the Fairfield system.

6.9 Acknowledgements
The authors thank David Thompson, P.Eng., at Loyalist Township for providing data and advice in the development of this paper. This research was financially supported by Queen’s University and the Natural Sciences and Engineering Research Council.
6.10 References


Climate change has been identified as a serious threat to human and economic security (Erwin et al. 2012). The developed world has begun to address climate change by means of policy measures such as carbon pricing (a carbon tax or cap-and-trade system) and economic discounting in project planning. Since the water industry is a major user of fossil-based electricity, policies such as a carbon tax and low discount rates can potentially stand to change the way water distribution systems are designed, operated, and rehabilitated. The research in this thesis has sought to examine the impact of climate change mitigation scenarios in the optimal WDS design/expansion, operation, and rehabilitation planning of water distribution networks.

### 7.1 Overall Research Contributions

The overall contributions of this research are listed below. The first 6 research contributions relate to the development of the single- and multi-objective optimization algorithms that account for GHG emissions in the solution of the design/expansion, operation, and rehabilitation planning problems. The remaining 2 research contributions relate to the new scenario analyses that were performed to examine the impact of climate change mitigation scenarios on energy use, GHG emissions, and design/expansion, operation, and rehabilitation decisions in the optimization of water distribution networks.
7.1.1 Model Development

**Contribution 1:** The first research contribution is the development of the single- and multi-objective optimization algorithms that account for GHG emissions in the solution of the water distribution network design/expansion, operation and rehabilitation planning problems.

**Contribution 2:** The second contribution is the development of a new gene-coding scheme to reduce the computational requirements to solve the optimal water distribution network operation and rehabilitation planning problems. The proposed event-based method (Chapters 5 and 6) reduces the length of each chromosome by 20 percent when compared to traditional approaches. The gene-coding scheme is an important contribution because it makes it feasible to solve the operation and rehabilitation optimization problems for large, complex networks.

**Contribution 3:** The third research contribution is the development of a new pump scheduling optimization approach that can model a Programmable Logic Controller (PLC) system that controls the real-time operation of pumps and reservoirs in a complex water transmission system (Chapter 3).

**Contribution 4:** The fourth research contribution is the inclusion of a pipe break forecasting model, a leakage forecasting model, and pipe wall roughness growth model in the water main rehabilitation optimization algorithms of Chapters 5 and 6. This is the first water main rehabilitation optimization model to include all three model types.

**Contribution 5:** The water distribution network rehabilitation algorithms of Chapters 5 and 6 are the first to consider the full range of water main rehabilitation decisions such as pipe duplication, pipe replacement, pipe lining, and new pipe installation.

**Contribution 6:** The sixth research contribution is the development of the graphical user interface (GUI) used for all the algorithms presented in this thesis. The GUI was designed to
facilitate the entry and management of the extensive data involved in the simulation and optimization of water distribution networks. The GUI was also designed to allow users without any programming knowledge to use with ease.

7.1.2 Scenario Analyses

**Contribution 7:** The optimization algorithms developed in this research were applied to two complex, real-world water systems. Previous research by Wu et al. (2010a, 2010b, 2012) examined GHG emissions in small, hypothetical systems. The consideration of real, complex systems in this research means that it could potentially contribute to the future evolution of climate change mitigation policies as they pertain to the Canadian water industry.

**Contribution 8:** The scenario analyses presented in the case studies considered the full range of demand conditions, including a 24-hour average day diurnal pattern, maximum hour demands, maximum day demands, and fire flow. Previous research by Wu et al. (2010a, 2010b, 2012) only considered the average day demand condition in its examination of GHG emissions in networks.

7.1.3 Research Findings in Case Studies

**Chapter 3:** The impacts of carbon mitigation scenarios on energy use and GHG emissions in Kamalsaleh water transmission system were investigated. The results for single-objective simulations indicated that carbon tax and discount rate have noticeable impact on the level of reservoir storages in the case study while it produces a small reduction in the GHG emission. The multi objective results indicated that the Pareto front shape (steepness) is affected by the discount rate and carbon tax where modest investment in the capital cost produces significant reduction in the operational costs. It should be noted that the results is only pertain to the KamalSaleh transmission system and more research is needed to examine the effectiveness of discount rate and carbon tax in reducing energy use and greenhouse gas emissions in low-lift transmission
system with different topographies, a range of water demand levels and diurnal patterns, a range of pipeline diameters, and a range of reservoir configurations.

Chapter 4 investigated the effect of proposed Canadian climate change mitigation policies on the energy use and GHG emissions in design and expansion of Fairfield water distribution system. Results indicated that the proposed discount rates and GHG taxes have no significant impact on the GHG emission. And the Fairfield WDS was not able to meet GHG reduction target set by the Canadian government. Time declining emission intensity factor, relatively short design period of the case study, and adequate hydraulic capacity in the Fairfield system to meet present and future demands were the major contributors to the insensitivity of GHG emission and energy use to the proposed policies. It worth mentioning that the results are limited to the Fairfield case study and more investigation is necessary to determine the effectiveness of the proposed polices in other networks in Canada.

Chapter 5 proposed the new event-based approach to find the optimal WDS rehabilitation planning in Fairfield network. It examined the effect of asset management strategies such as discounting and budget management on the capital and operational cost of rehabilitation solutions. The results suggested that applying a budget constraint prohibited the search process from investing early and heavily in pipe rehabilitation with a resulting increase in cost linked to pipe leakage, pipe breaks, and energy use. Moreover, a sensitivity analysis showed that water demand, leakage and break growth rates can have a moderate to significant impact on capital and operational costs. The results are limited to Fairfield WSD and more investigations are necessary to understand the impact of asset management strategies on the distribution of the water main rehabilitation decisions especially when other network components such as pumps and tanks are included in the search space.
Chapter 6 for the first time studied the effects of proposed carbon mitigation policies on optimal rehabilitation planning of a WDS. The proposed model was applied to Fairfield network and results indicated that low discount rate and high carbon tax have small impact of GHG reduction while significantly decrease the leakage and pipe breaks. Further low discount rate and high carbon tax encouraged the optimization engine to invest early in the planning period to reduce leakage, energy, GHG costs, and pipe breaks. The results are limited to Fairfield WDS; additional research could shed light on the effect of the carbon mitigation policies on the rehabilitation options while renewing pump stations and tanks are considered.

7.2 Research Limitations

The embodied energy and GHG emissions linked to the material extraction, material production, and manufacturing of water main materials such as PVC was not included in the optimization algorithms for lack of data in Canada.

Only decision variables that pertain to water mains were optimized in the network design/expansion and rehabilitation planning models of Chapters 4, 5, and 6. Other system components such as pumps and elevated tanks were not optimized in these models. This is justified on the grounds that water main assets often account for the largest asset value in many networks. Further, no additional pumping station and elevated tank facilities were required in the Fairfield water distribution network to meet forecasted future demands (Thompson 2011).

Given the large search space in the network design/expansion, operation, and rehabilitation planning problems of Chapters 3, 4, 5, and 6, a stopping criterion based on a defined number of generations was imposed on the optimized solutions. The implication is that the solutions generated in the single-objective optimization are near-optimal solutions. Similarly, the Pareto-
optimal solutions generated in the multi-objective optimization are near optimal Pareto front. There is still no universally accepted stopping criterion for heuristic search algorithms.

There are number of variables at play in the solution of the network design/expansion, operation, and rehabilitation planning problems whose uncertainty was not characterized in the scenario and sensitivity analyses of this thesis. Uncertain financial parameters such as electricity price, water price, and budget limit were not considered in the analyses. Water demand and hydraulic parameters such as peak demand factors and minimum and maximum pressure were not considered in the analyses. Simulation variables such as expected service life of water main, and lag times between rehabilitation events were not considered in the analyses. Genetic algorithm optimization parameters such as population size, mutation and crossover probabilities, number of evaluations were not considered in the analyses.

7.3 Recommendation for Future Work

Based on the research limitations highlighted above, future research should focus on making advancements in the following areas:

Area 1: Future work could consider embodied energy use and GHG emissions associated with material extraction, material production, and the manufacturing of system components such as water mains (of different materials), pumps, elevated tanks, and reservoirs. Considering embodied energy use and GHG emissions would help municipalities and water utilities better understand the trade-offs in energy use and GHG emissions linked to capital infrastructure investments and pumping water in a system over a specified planning horizon.

Area 2: Future work could consider an additional number of decisions variables to optimize such as the sizing and sitting of pumps, elevated tanks, and reservoirs. While this would further increase computational expense, it would allow municipalities and water utilities to better
understand the effects of making major capital investments in new pumping station and tank facilities on the energy use and GHG emissions generate by their systems.

Area 3: Future work should also provide general recommendations on the practical number of optimization generations required to find near-optimal solutions in the network design/expansion, operation, and rehabilitation planning problems.

Area 4: Future work could focus on performing more comprehensive sensitivity analyses to examine the impact of uncertain financial, pipe aging, water demand, hydraulic, and other variables on the system costs, energy use, and GHG emissions of networks.

Area 5: There is a need to apply the optimization models developed in this thesis to other real-world water distribution networks to better establish the relationship between key system properties (e.g., topography, age of water main assets, etc.) and energy use and GHG emissions in other complex, real-world systems. This knowledge is necessary to develop best practices that municipalities and water utilities can use to guide their capital infrastructure budget planning and achieve tangible reductions in operating and other systems costs and energy use.

7.4 References


<http://www.nationaldefensemagazine.org/archive/2012/November/Pages/TopFiveThreats toNationalSecurityintheComingDecade.aspx>


Appendix A
OptiNET Validation Results

Summary of test functions

All of the optimization benchmark problems that have been used to validate the OptiNET are listed in the following two tables. The first table contains the benchmarks without constraint and the second table includes the benchmarks with constraints.

| Table A-1 Benchmarks without constraint used to validate OptiNET |
|-----------------|-----------------|-----------------|-----------------|
| Problem | \( n \) | Variable bounds | Objective functions | Optimal solutions | Comments |
| SCH | 1 | \([-10^n, 10^n]\) | \(f_1(x) = x^2\) \(f_2(x) = (x - 2)^2\) | \(x \in [0, 2]\) | convex |
| FON | 3 | \([-4, 4]\) | \(f_1(x) = 1 - \exp \left(- \sum_{i=1}^{3} \left(x_i - \frac{1}{\sqrt{3}} \right)^2 \right)\) \(f_2(x) = 1 - \exp \left(- \sum_{i=1}^{3} \left(x_i + \frac{1}{\sqrt{3}} \right)^2 \right)\) | \(x_1 = x_2 = x_3\) | nonconvex |
| ZDT1 | 30 | \([0, 1]\) | \(f_1(x) = x_1\) \(f_2(x) = g(x) \left[ 1 - \sqrt{x_1 / g(x)} \right] \) \(g(x) = 1 + 9 \sum_{i=2}^{n} x_i / (n - 1)\) | | convex |
| ZDT2 | 30 | \([0, 1]\) | \(f_1(x) = x_1\) \(f_2(x) = g(x) \left[ 1 - (x_1 / g(x))^2 \right] \) \(g(x) = 1 + 9 \sum_{i=2}^{n} x_i / (n - 1)\) | \(x_1 = 0, x_i = 0, i = 2, \ldots, n\) | nonconvex |
| ZDT3 | 30 | \([0, 1]\) | \(f_1(x) = x_1\) \(f_2(x) = g(x) \left[ 1 - \sqrt{x_1 / g(x)} - \frac{x_1}{10n} \sin(10\pi x_1) \right] \) \(g(x) = 1 + 9 \sum_{i=2}^{n} x_i / (n - 1)\) | \(x_1 = 0, x_i = 0, i = 2, \ldots, n\) | convex, disconnected |

All objective functions are to be minimized.


Table A-2 Benchmarks with constraints used to validate OptiNET

<table>
<thead>
<tr>
<th>Problem</th>
<th>( n )</th>
<th>Variable bounds</th>
<th>Objective functions</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONSTR</td>
<td>2</td>
<td>( x_1 \in [0.1, 1.0] ) ( x_2 \in [0.5] )</td>
<td>( f_1(x) = x_1 ) ( f_2(x) = (1 + x_2)/x_1 )</td>
<td>( g_1(x) = x_2 + 5x_1 \geq 6 ) ( g_2(x) = -x_2 + 5x_1 \geq 1 )</td>
</tr>
<tr>
<td>SRN</td>
<td>2</td>
<td>( x_i \in [-20, 20] ) ( i = 1, 2 )</td>
<td>( f_1(x) = (x_1 - 2)^2 + (x_2 - 1)^2 + 2 ) ( f_2(x) = 9x_1 - (x_2 - 1)^2 )</td>
<td>( g_1(x) = x_1^2 + x_2^2 \leq 225 ) ( g_2(x) = x_1 - 3x_2 \leq -10 )</td>
</tr>
<tr>
<td>TNK</td>
<td>2</td>
<td>( x_i \in [0, \pi] ) ( i = 1, 2 )</td>
<td>( f_1(x) = x_1 ) ( f_2(x) = x_2 )</td>
<td>( g_1(x) = -x_1^2 - x_2^2 + 1 + 0.1 \cos(16 \tan(x_1/x_2)) \leq 0 ) ( g_2(x) = (x_1 - 0.5)^2 + (x_2 - 0.5)^2 \leq 0.5 )</td>
</tr>
</tbody>
</table>

All objective functions are to be minimized.


OptiNET test results vs. NSGA-II

![Figure A-1 Non-dominated Pareto front obtained on SCH benchmark](image)

213
Figure A- 2 Non-dominated Pareto front obtained on FON benchmark

Figure A- 3 Non-dominated Pareto front obtained on ZDT1 benchmark
Figure A- 4 Non-dominated Pareto front obtained on ZDT2 benchmark

Figure A- 5 Non-dominated Pareto front obtained on ZDT3 benchmark
Figure A-6 Non-dominated Pareto front obtained on Constr benchmark

Figure A-7 Non-dominated Pareto front obtained on SRN benchmark
Figure A-8 Non-dominated Pareto front obtained on TNK benchmark
Appendix B
Parallel Processing

Abstract
A high level of computational power is often needed to solve real-world engineering problems. The introduction of multi-core Central Processing Units (CPUs) opened a new window for small companies and academic researchers to benefit from high performance computing. OptiNET benefits from two different parallel processing libraries, the Message Passing Interface (MPI) and Task Parallel Library (TPL). In this appendix both of these libraries are applied to find the optimal rehabilitation plane for a Fairfield water distribution system. The time required to evaluate all solutions in the last generation were measured for increasing number of cores in both approaches and compared.

Introduction
The introduction of multi-core Central Processing Units (CPUs) in 2005 revolutionized the software industry. Since then the demand for multi-core computing has increased and it has become progressively less expensive. For example, one can now purchase a desktop computer with 24 cores for less than $3,000. Suddenly, parallel computing has become available to a much broader range of users, including consulting engineers, through new programming interfaces and toolboxes.

Increasingly, engineers are turning to optimization to plan the design, expansion, and rehabilitation of water distribution systems. High computational power is required to find the optimal solution in real networks which tend to have a large number of pipes and components and thus impose long run times on a network solver to evaluate the hydraulic and/or water quality conditions. Optimization is one of the best examples of algorithms in which tasks could be run in
parallel. In fact, optimization algorithms are known as “attractively” parallel algorithms (Microsoft Corporation 2008). Since these algorithms are computationally-intensive, they are best solved on multi-cores computers or a cluster machine (Microsoft Corporation 2008).

There are several parallel programming interfaces available in the market and most of them are open source. The objective of this paper is to present the parallelization of code to solve the multi-objective optimization of a real-world water distribution network in Amherstview, Ontario, Canada. Two well-known open source interfaces, TPL and MPI.net, were used to solve the multi-objective problem, with significant increases in computational speed. Both methods will be introduced and discussed in the paper, and the pseudo-code implementation used to parallelize the optimization algorithm will be discussed.

**Methodology/Process**

**Parallel Processing**

Parallel processing is the ability to do multiple operations or tasks simultaneously. This term is frequently used in the human cognition context to discuss brain functionalities such as vision. The simultaneous use of several CPUs to execute a task or a program is called parallel processing. The idea is to divide a computational task among multiple CPUs to increase the speed of computations. There are well-known problems in water distribution systems analysis that can benefit from parallel computing. Examples include Monte Carlo Simulation, evolutionary algorithms (e.g., genetic algorithms), ant colony optimization, and particle swarm optimization. There are several tools and programming interfaces available such as Task Parallel Library (TPL) and Message Passing Interface (MPI) to allow users to perform parallel processing operations.
with a multi-core cluster machine. These tools will be introduced and discussed in the follow section.

**Message Passing Interface (MPI)**

Message Passing Interface (MPI) is a language-independent communication protocol used to perform parallel computing operations on a multi-core machine. The MPI interface handles all communication protocols and semantic specifications between CPUs in a multi-core machine. MPI was introduced in 1992 by Aoyama and Nakano (1999). Most MPI implementations are open source and consist of a set of routines which are called directly from C, C++, FORTRAN, C#, Java, and Python code.

MPI programs are usually written as Single Program Multiple Data (SPMD) applications. In this application, each CPU (or core in a multi-core machine) is running the same software program but with a different set of data. For example, consider how a single-core and multi-core machine would perform genetic algorithm operations in the least-cost design of a water distribution system. With a population of 1,200 chromosomes, a single-core machine would have to simulate the hydraulic conditions of all solutions (or chromosomes) with EPANET (Rossman 2000). In contrast, a multi-core machine made up of 24 cores would divide the EPANET simulations equally among its 24 cores and so each core would only be expected to perform 50 simulations. Although it is not necessary to divide computational load equally among cores, it often helps achieve a more synchronous code.

MPI supports the SPMD application by allowing the user to execute the same software program on different machines or running several copies of the program (process) on the same machine or a combination of both methods. The only difference among processes is that a specific rank is uniquely assigned to each process. Using this rank, MPI processes can communicate and can
behave differently. In the GA example, the process with the first rank (rank 0) is responsible for dividing the population into several smaller sub-populations and for sending them to other processes to evaluate.

There are several types of communications required in parallel processing: (i) one-to-one, (ii) one-to-all, and (iii) all-to-all. All of them are supported in MPI. One-to-one communication is also called point-to-point which is the most basic form of communication. This communication mode allows the process to send a message (e.g., data) to another process. Each message has a source and a target process identified by their rank and it has a tag which is normally used to identify the type of the data being passed. Pseudo code for this mode of communication can be structured as follows:

\[
\text{Comm.Send(Data, Target, Tag)}
\]
\[
\text{Comm.Receive(Data, Source, Tag)}
\]

In which Comm is the communicator object, Data is the variable being passed to the target process. Target, is the process rank which receives the data. Source is the process rank which sends the data, and Tag is the integer number which could represent the data type.

Consider a process which in its first rank sends some data to the next process. Pseudo code for this program is written as follows:

\[
\text{If(Comm.rank == 0)}
\]
\[
\quad \{ \text{Comm.Send("Test", Comm.rank + 1, 0)} \}
\]
\[
\text{Else}
\]
\[
\quad \{\text{Comm.Receive(Data, 0, 0) }\}
\]
In this code, the process with rank 0 (the root process) sends a string “Test” to the ranks 1 and rank 1 receives “Test” form rank 0 and stores it in the variable named “Data”. One-to-all communication or “Broadcast” takes a value and sends it to all other processes. This mode of communication takes two arguments; the first one contains the value to send at the root process and it stores the transmitted value in other processes. The second argument is the rank of the root process. For instance, in the pseudo code indicated below, a variable Data will be broadcast to all other process from the root process which has a rank equal to 3.

\[\text{Comm.Broadcast(Data, 3)}\]

There are other versions of Broadcast such as “Scatter” which simply divide the data into smaller pieces and then send each piece to one process. The root process provides an array of values in which the ith value will be sent to the process with rank ith allowing the root to distribute different tasks to each of the other processes.

In the contrary to the Broadcast mode of communication, the “Gather” mode of communication collects data provided by all other processes in the root process. It has two arguments; the first one is the value which is supposed to be collected and the second is the root process rank. In the following pseudo code, a variable named “Data” is collected from all processes and it is stored in the array called “TotalData” in the process with rank 0:

\[\text{Array[] TotalData = Comm.Gather(Data,0)}\]

The all-to-all communicator transmits data from every process to every other process. The following pseudo code demonstrates the functionality of this mode of communication:
Array[] Results = Comm.AllToAll(Data[])

Using these modes of communication, one can easily distribute the computational load for algorithms such as genetic algorithms and Monte Carlo Simulation. The following is the pseudo code required to evaluate all of the solutions in one generation in the genetic algorithm example (mentioned above) to solve the least-cost water distribution network:

Comm.scatter(Solutions[], 0)
For I = 0 to n
    Result[I] = evaluate(Solutions[I])
Next I
Array[] Results = Comm.Gather(Result,0)

From the root process, the first line of the pseudo code sends solutions to other processes. In the loop, each solution is evaluated by the function call “evaluate” and the result for each solution is saved in the array called “Result”. The results from each process are then sent back to the root process and stored in the array called “Results”.

It is obvious from the pseudo code above that this is the MPI responsibility to make sure all the data were transmitted correctly and all the process are working fine and synchronously. But it is still the programmer’s job to assign the variables to send through MPI functions and to handle different processes. Therefore writing a code with MPI needs to have a good understanding of data structure and robust knowledge of algorithm development. MPI codes are designed to work in every environment but they are mainly optimized to work on clusters. Moreover, MPI codes
can run on ordinary machines without high performance computing capabilities and multiple cores.

**Task Parallel Library, TPL**

Task Parallel Libraries (TPL) provide the programming infrastructure to use multi-core machines to improve the computational performance of a program. TPL is the task parallelism component to the ‘.Net’ framework developed by Microsoft Research and Microsoft Common Language Runtime (CRL). The library was released in version 4.0 of the ‘.Net’ framework. It exposes parallel constructs like Parallel “For” and “ForEach” loops using regular method calls (D. Leijen and J. Hall 2007).

TPL is designed to use with multi-core machines in the managed codes and it does not support distributed memory architecture usually found in clusters. TPL allows users to develop their code in a sequential manner while still providing the benefit of parallel processing. It should be noted that the functions which are supposed to run in parallel should be independent from each other.

Unlike MPI which works with most programming frameworks, TPL is designed to work within the ‘.Net’ framework. It can be used within all ‘.Net’ languages including C# and Visual Basic. All parallelism is expressed using general call methods. For instance, consider the following sequential code to evaluate all solutions in a generation in GA example (mentioned before) written in C# language:

```csharp
for (int i = 0; i < 100; i++) {
    results[i] = evaluate(Generation[i]) ;
}
```

Since evaluating each solution is independent from others, one can use TPL to benefit from potential parallelism as follows:
Parallel.For(0, 100, delegate(int i) {
    results[i] = evaluate(Generation[i]);
});

Note that “Parallel.For” is a normal call method. It takes three arguments in which the first argument is where the counter begins, the second one is where the counter ends and the last one is the delegate expression which captures the unchanged code from previous sequential code. TPL divides the computational load between available cores and ensures that parallelism is employed to run the program code. The demonstrated codes are the actual codes required to convert a sequential program to a parallel program. These codes illustrate the simplicity of using TPL. TPL includes sophisticated methods to handle dynamic load distribution as well but these methods are beyond the scope of this paper.

**Parallelism in Practice**

To examine the effectiveness of MPI and TLP in practice, a water distribution system rehabilitation optimization problem was defined and a genetic algorithm was used to solve it. The problem is developed to find network rehabilitation solutions that minimize the capital costs and minimize the operational costs simultaneously for a planning period of 20 years. Equation (1 and 2) shows the objective functions in mathematical format.

\[
Obj1 = \text{Min}(CC) = \sum_{t=0}^{20} \sum_{p=1}^{np} \left( RC_{t,p} + DC_{t,p} + LC_{t,p} + NP_{t,p} \right) 
\]

\[
Obj2 = \text{Min}(OC) = \sum_{t=0}^{20} \sum_{p=1}^{np} \left( LkC_{t,p} + BC_{t,p} \right) + \sum_{i=1}^{50} EC_i 
\]
In which $CC$ is the capital costs, $OC$ is the Operational cost, $t$ is time in year, $p$ is the pipe number, $RC_{t,p}$ is replacement cost for the $p^{th}$ pipe in the $t^{th}$ year, $DC_{t,p}$ is pipe duplication cost, $LC_{t,p}$ is Lining cost, $NC_{t,p}$ is new pipe cost, $LkC_{t,p}$ is the cost of lost water, $BC_{t,p}$ is break repair cost, and finally $EC_t$ is the energy cost. The optimization was subject to operational velocity and pressure constraints. The goal was to find the time, type and the place of rehabilitation activities in the network. Available rehabilitation technologies considered in this problem were new pipe installation, replacement of old pipes, pipe duplication, and pipe re-lining (cement-mortar lining).

![Figure B-1 Fairfield water distribution system](image)

The code was developed based on a specific multi-objective genetic algorithm named the non-dominated sorting genetic algorithm version II (NSGA-II) (Deb 2002). The NSGA-II was combined with the EPANet toolkit (Rossman 2000) to simulate the hydraulics of the Fairfield
water distribution network in Eastern Ontario, Canada. This network provides drinking water to the Town of Amherstview and the Town of Odessa which have a combined population of approximately 15,000 people (Roshani et al. 2012). The all-pipes model (400 links) of the Fairfield system (Figure B-1) consists of existing pipes and new pipes in future-growth areas.

In the optimization application, pipe rehabilitation events were applied in each year of the 20-year study period. For this reason, the hydraulic conditions in the Fairfield network were simulated in each year of the 20-year period. Energy costs were characterized by running a 24-hour extended period simulation in each year of the 20-year period. A total of 20 extended period simulations were performed for each rehabilitation solution considered in the optimization. Additional steady-state simulations were run each 10 years to characterize pressures during maximum day demand and fire flows at three critical locations. The details of the hydraulic model, pipe break model, leak model, and pipe aging model are discussed in Roshani and Filion (2012).

The parallelized optimization algorithm was solved with both TPL and MPI interfaces and applied to the Fairfield network. The problem was solved with an increasing number of cores (1, 2, 4, 6, 8, 10, 12, 16, 20, 24, 48, 60, 80 and 120) to show the effect of parallelization in increasing computational speed. A GA population of 1,200 chromosomes was adopted in the optimization problem. Since GA operators such as crossover, mutation, and selection are random operators, it is impossible to obtain the same exact chromosomes (solutions) in different generation therefore computational load in each scenario would be different. The authors ensured that each run (with a specified number of cores) had a similar computational load by comparing the run time of the 1000th generation in the optimization problem.
Results/Outcomes

A ‘.Net’ implementation of MsMPI was used and C# was chosen as the preferred programming language in the optimization application. A graphical user interface for data entry and GA progress monitoring was developed (Figure B-2). Task Parallel Library in Visual Studio 2010 was used directly in C#. It should be noted that although Visual Studio is proprietary but both of MPI.net and TPL are free and could be used with other .net language including Visual Basic.

A cluster machine with five nodes was used to run the optimization program. Each machine has 2 sockets and each socket has 12 cores. Therefore each node has 24 cores and there are a total of 120 available cores. Windows HPC Server 2008 R2 serves as the operating system on all of the machines. Two networking switches have been used to transfer data. A 10 Gigabit switch serves as an application network between nodes exclusively for MPI application. And a one gigabit

![Figure B-2 Part of the Graphical User Interface, GUI, developed to prepare the optimization models and to control the cluster machine](image-url)
switch was used to manage nodes by the operating system. Separating application network and operating network reduced the networking overload in the cluster (Juethner 2011). It should be noted that these network switches were used in MPI model and not in TPL model.

The run times to evaluate all 1,200 solutions in the 1000th generation were measured and are indicated in Figure B-3. Solutions were evaluated with 1 to 120 cores with the MPI model and with 1 to 24 cores with the TPL model. As previously mentioned, the TLP model is designed to utilize multi-core CPUs on one machine and since there are only 24 cores in one node, it was not possible to run the TLP model with more than 24 cores.

![ Required Time To Evaluate One Generation ]

Figure B-3 Required time to evaluate all solutions in one generation with a different number of cores.

As shown in Figure B-3, the MPI and TPL models used with one core (sequential mode) produced run times of 11,572s and 11,575s. Doubling the cores to 2 and then to 4 decreased the run time to almost half and then to a quarter of the run time of a single core. Figure B-4 indicates
that the run time observed with 24 cores was almost 14 times less than the run time observed with a single core. There is a small difference between MPI and TPL run times owing to difference in their architecture. This difference increases by adding the number of cores which is probably caused by increasing the operating system overload.

Although it is expected that using 120 cores should reduce the required time by a factor of 120, this is not likely to be observed in practice. This is mainly because of networking and operating system overload. Our platform accelerated the running time by a factor of 76. A computing time of 151 seconds was needed to evaluate one generation. A computing time of 1.75 days was needed to simulate 1,000 generations to find the near-optimal Pareto front as compared to a computing time of 134 days had sequential programming been used.

![Running Acceleration by Increasing the Number of Cores](image)

*Figure B-4 Running acceleration achieved with the parallelism.*
Summary

The paper presented a method of code parallelization to solve the multi-objective optimization of a real-world water distribution network in Fairfield, Ontario, Canada. Two well-known open source interfaces, TPL and MPI.net, were used to solve the multi-objective problem, with significant increases in computational speed. Both TPL and MPI methods were introduced, discussed, and compared against each other and against a serial computing control example. Two models were developed based on established parallelism concepts. The advantages and disadvantages of each method were discussed. Although it is more difficult to develop an algorithm for MPI codes, such a code can be run on a cluster of machines with almost unlimited computational power. While the TLP method is simpler to develop, it is limited to one machine. The results indicated that using MPI and running the model on 120 cores could speed up the calculation time by a factor of 76 as compared to sequential programming. TLP can speed up calculations by a factor of 11 on a single machine with 24 cores.

References


Appendix C
The Optimization Specifications

The number of generations and number of solutions in each generation could be found in the Table C-1

*Table C-1 The optimization specifications in each chapter.*

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Simulations</th>
<th>Number Populations</th>
<th>Number of Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 3</td>
<td>Single Objective</td>
<td>2000</td>
<td>1600</td>
</tr>
<tr>
<td></td>
<td>Multi Objectives</td>
<td>2000</td>
<td>1600</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Single Objective</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Multi Objectives</td>
<td>10000</td>
<td>240</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Multi Objectives</td>
<td>10000</td>
<td>240</td>
</tr>
</tbody>
</table>