Examining the Relationship between Pumping Energy and Geographically-Targeted Water Conservation Measures in Municipal Water Distribution Networks

by

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Abstract

Municipal water distribution systems are operated and maintained by utilities whose first priority is the safe and reliable provision of drinking water to consumers. The cost to move and treat water through distribution networks is significant and can account for up to 80% of a utility’s energy costs. As these networks age, operating and maintenance costs continue to increase due to higher incidences of leaks and breaks and increased pipe friction leading to higher energy use. Many utilities are considering water conservation as a strategy to reducing their energy consumption by reducing the amount of water being pumped and treated in their jurisdictions.

This work studies the pumping energy response of a distribution system when water conservation strategies are implemented in small geographic areas in the network. A water conservation plan is tailored to each defined area by specifying which conservation measures are feasible to implement, desired by the customer, and are attractive to the utility based on a potential return on investment in the form of reduced electricity bills to pump and treat water. Energy intensity and energy elasticity indicators are developed to assess the mechanical energy used in a network to distribute water to end-users. A case study for the City of Kingston water distribution system is presented. The distribution system studied indicated that when water conservation strategies produced marginal water savings, the energy response was inelastic to changes in water demand. The amount of energy required to move one cubic metre of water through the network increased with higher water savings because the percent savings of water was higher than the percent savings of pumping energy.
To Granddad

for your constant love and support, inspiring me to dream big and see the world, and teaching me to live life to the fullest every day

“Watch out world, here I come.”
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CHAPTER 1

Introduction

1.1 Motivation

Governing bodies and utility operators for North American water infrastructure are likely to be faced with difficult challenges that affect their current management practices and operations. Aging pipes in distribution networks are producing high levels of leakages and breaks that can reduce the quality and reliability of potable water that reach customers (Colombo and Karney 2002). As these networks age, operating and maintenance costs continue to increase (Colombo and Karney 2002) yet municipalities are expected to maintain a safe and reliable water supply to customers on limited budgets. The system capacity in many municipalities must also be expanded to account for growth in urban centres, but investments toward maintaining existing infrastructure has proved insufficient; a 2007 study by the Federation of Canadian Municipalities found that the water infrastructure deficit – the money required to repair and replace the network – is estimated to be $31 billion (Mirza 2007). This estimate does not include the cost of future needs, estimated to be $56.6 billion (Mirza 2007). These statistics create a strong argument for reducing the water demand in drinking water distribution networks through demand management. Of importance is that a significant cost of operating distribution systems is the energy requirements for pumping. A survey by the Electric Power Research Institute finds that 80% of electricity requirements for a system are for distribution and water processing (EPRI 2002), and account for 4% of national electricity use in the US (EPRI 2002). These facts about that the water industry has two outcomes relevant to this study: (1) many municipal utilities are challenged by the ongoing maintenance and repairs of their system, compounded by the future
infrastructure needs to meet growth and demand, and; (2) by reducing the water demand of a network, pumping energy requirements can be reduced. There is room for engineers and utility management to improve the water and energy efficiency of their systems, but the significant challenge continues to be balancing financial constraints without compromising the safety and reliability of infrastructure systems. The solutions to increasing the water and energy efficiency of water distribution systems (WDSs) will likely require new planning strategies that look beyond supply-side management. Historically, WDSs were designed based on supply-side management, ensuring that the network could meet consumer needs while maintaining a high level of safety and reliability. Network capacity was built to meet the projected future needs of a municipality. However, in light of the recent recognition of higher energy prices, researchers and practitioners are considering how municipal utilities can structure their operations and management to both reduce costs and energy and water consumption. More recently, utilities have started to practice demand-side management. Demand-side management refers to any practice that reduces the amount of potable water being drawn from the network at a given time, such as reduced end-user demand (through attitude changes, low-flow fixtures/appliances, rainwater harvesting, greywater reuse, etc.), reduced leakage rates, or shifting use to off-peak periods. Many governments and municipalities have indeed taken the initiative to create comprehensive water conservation plans and targets. In the next section, select examples that provide evidence of Ontario policies at the provincial and municipal level that are implementing water conservation plans.

1.1.1 Province of Ontario

In November 2010, the province of Ontario enacted the Water Opportunities and Water Conservation Act (WOA) (2010) with conservation objectives for the Ontario water sector such
as strengthening collaborations between academics, industry and government, increasing Ontario’s water use efficiency through conservation measures and municipal infrastructure planning, and promoting the development of Ontario water technologies and services. Under the Act, the Water Technology Acceleration Project (WaterTAP) targets collaboration between academia, industry and government to promote water conservation and economic growth in the province (Government of Ontario 2010). The Act is largely an economic stimulus package, providing funding opportunities for projects that target water conservation and develop clean technologies for the water and wastewater industries. In 2011, the Government of Ontario committed $30 million for municipal water sustainability planning and education and public awareness for water conservation through the WOA (CNW 2011).

1.1.2 City of Toronto

The City of Toronto sets a strong example of water conservation at the municipal level. In 2003, Toronto enacted the Water Efficiency Plan (WEP), aimed at reducing municipal water use by 15% by 2011 by promoting a variety of water conservation and efficiency measures (toilet replacement, clothes washer replacement, water audits, leak detection, education, etc.) (City of Toronto 2003). A 2011 update to the plan reported a 14% decrease in average annual day demand between 2001 and 2010, accounting for population and employment growth. The success of the program was attributed to factor such as successful plan implementation, lower than expected growth, technological improvements to water saving toilets and washers, customer price sensitivity, wetter summers and public education programs (Toronto Water 2011).

1.1.3 City of Guelph
The City of Guelph has also shown a strong commitment to water conservation through their Water Conservation and Efficiency Strategy, originated in 1999 and most recently updated in May 2009. Stemming from the 1999 Strategy, the City of Guelph implemented rebate programs such as the Royal Flush Toilet Program (2003), Smart Wash Clothes Water Rebate Pilot Program (2008), ICI Water Capacity Buyback Program (2007), outdoor water use restrictions (2001), Landscape Assessment Pilot Program (2008), Facility Water Efficiency Retrofits (2001), and numerous public education and outreach programs (City of Guelph 2009). The cumulative results from the programs were 1,123 m$^3$/day (409,895 m$^3$/year) between 2003 and 2008, or a decline in gross water demand in 17% from 444 litres per capita per day (lpcd) to 370 lpcd from 1999 to 2007, respectively (City of Guelph 2009). The 10-year program implementation was estimated at $20,293,086 making the cost per litre saved equal to $2.31. Having assumed an average cost of $4.00 per additional litre for water and wastewater capacity in the City of Guelph, the conservation program is 42% more cost effective than increasing system capacity (City of Guelph).

1.1.4 City of Kingston

Utilities Kingston currently offers 1,000 rain barrels at cost through their Rain Barrel Program each spring and has a toilet rebate program for managers or owners of multi-residential buildings (UK 2013). The Water Efficiency Retrofit Incentive Program offers industrial, commercial, and institutional customers an incentive of $5/m$^3$ of permanent annual combined water and wastewater savings to a maximum of 20% of project costs (UK 2013). The Utility also runs various water conservation education programs and has a demonstrative water conservation garden on site. The City of Kingston does not currently have a water conservation program or water conservation targets in place.
1.2 Water Conservation Measures Implemented in Canadian Water Systems

Typically, water conservation programs use two approaches: policy approaches (initiating new policies, public conservation campaigns, pricing mechanisms, watering restrictions, and education) and technological approaches (installing new fixtures and appliances that reduce water use without requiring a direct behavioural change). The focus of this work is on technological approaches. Typical programs can include rebates, incentives, or education and awareness campaigns for low-flush toilets, low-flow faucets and showerheads, water-efficient laundry machines and dishwashers, and outdoor water saving devices such as rain barrels. Figure 1.1 shows a typical breakdown of indoor water use in a Canadian household.

![Pie chart showing indoor water use breakdown for Canadian households](image)

Figure 1.1: Indoor water use breakdown for Canadian households (Environment Canada 2011)

1.3 Partnership with Utilities Kingston

The collaboration with Utilities Kingston (UK) was initiated after UK’s energy conservation program recognised the potential to benefit from energy conservation rebate programs. UK can
benefit from Ontario Power Authority (OPA) rebates by quantifying the energy savings associated with various water saving fixtures and appliances. The OPA launched the saveONenergy conservation program (OPA 2010) for homes and businesses with the goal of reducing electricity use. The OPA offers incentives to homeowners, businesses, industries, governments and institutions, etc. to reduce their electricity use through retrofit programs, rebates for high-efficiency appliances and heating/cooling systems, shifting electricity use to off-peak times, etc. Utilities Kingston, through Kingston Hydro, is involved in the saveONenergy program to reduce electricity use within the City of Kingston. By identifying water conservation measures that meet prescriptive per-unit requirements for energy conservation, UK can benefit from the saveONenergy program while reducing water use in the system. The work presented in this thesis is intended to support UK’s energy reduction targets by assessing the energy savings achievable through different water conservation strategies. The methodology contained within the thesis is therefore intended as a practical tool for utilities and municipalities looking to assess the effectiveness of water conservation programs in reducing their water consumption, environmental footprint, or energy requirements.

1.4 Thesis objectives

The thesis objectives are to:

1. Create a water conservation planning framework that prioritizes water saving initiatives based on the energy savings within the network.

2. Include the consideration of socio-economic and demographic factors into the water conservation planning framework.
3. Develop a household water conservation model on a fixture-by-fixture level.

4. Develop a set of indicators that can assess the effectiveness of water conservation strategies with respect to water and energy savings in a network.

5. Identify feasible water conservation measures for socio-economic and demographic areas in the City of Kingston with the water and energy savings indicators in Step 4.

1.5 Thesis Contributions

The novel contribution of this thesis is the development of a water conservation planning framework that quantifies energy and water reductions in small geographic areas. The framework includes socio-economic and demographic considerations to provide a realistic case study of an existing municipality. The contributions to the field of water conservation and demand-side management of WDSs are:

1. A municipal planning framework that prioritizes water conservation initiatives based on reduced water consumption and energy use.

2. The inclusion of socio-economic and demographic factors in the water conservation planning for a distribution network.

3. A household level analysis of potential water and energy savings based on a fixture-by-fixture water conservation model.

4. The development and application of new metrics to assess the pumping energy of water distribution on small-scale areas in a distribution network.

5. Results that link WDS pumping energy requirements to geographically-targeted water conservation strategies.
1.6 Organization

The thesis is structured as follows:

Chapter 2 is a literature review of water conservation planning for centralized urban WDSs. The work in Chapter 2 is in part adapted from a journal paper that has been accepted to the Journal of Water Resources Planning and Management entitled, “Regulatory, Analysis, and Decision Support Challenges to Reduce Environmental Impact in the Design and Operation of Water Distribution Networks,” which reviewed the challenges researchers, planners and decision makers currently face in incorporating sustainability objectives into the planning and design of centralised WDSs. The motivation for the paper was to review the current state of water resource management and planning and to identify what feasible steps can be taken by decision makers and planners to reduce the environmental burden associated with WDS design, operation, and disposal. Major modifications have been made and new inclusions added to focus on water conservation.

The research methodology and case study results are presented in Chapter 3. In this chapter, the water conservation planning framework is developed in detail. The inclusion and selection of socio-economic and demographic factors in the planning process is explained. A household water use model is presented and adopted to calculate potable water use based on typical household fixtures and consumption patterns. Indicators that are used to assess the water and energy savings associated various conservation initiatives are developed. The methodology is then applied to a case study for the City of Kingston’s Utilities Kingston (UK). The study considers geographically-targeted water conservation within Kingston’s distribution system that is based on selected conservation initiatives for each socio-economic and demographic region.
Results are presented through three types of indicators: energy intensity, energy elasticity, and water and energy percent savings. A discussion about the role of geographic location and network components on energy savings in municipal water systems is discussed.

Chapter 4 concludes the thesis by providing an overall discussion of the results and assessment of the contributions made through the work. The author suggests future avenues of research based on the thesis results that could contribute to the field of water conservation and demand-side and management of WDSs.

1.7 Publications

The work from this thesis was published in papers and articles submitted to peer-reviewed international conferences and journals. The following summarizes the publications that have arisen from the completion of this thesis:


1.8 References


CHAPTER 2
Literature Review

2.1 Introduction

Water conservation, and more broadly environmental regulation, is often developed after a crisis such as a prolonged drought or limited infrastructure capacity, or when there is economic incentive to reconfigure current operations. Another driver is sometimes public awareness, where constituents put pressure on governments to monitor a particular concern or where other model utilities/governments shine light on how they have improved their operations to reduce resource consumption. Thirdly, independent homeowners, landlords, business owners, or municipal organizations are often motivated to participate in resource conservation because of their belief in environmental protection beliefs and/or because they see the investment as beneficial through savings in operational expenses. The author identifies two on-going issues that are likely to drive policies, and more hopefully regulation, for water and energy conservation. North American water infrastructure, on average, has reached an age where the replacement rates of pipes will need to increase to continue to provide an acceptable level of reliability and safety (ASCE 2009). Further, strained water infrastructure due to increasing demand in city centers and climate change has led many developed countries to include environmental protection in their policies and regulations (Oldford and Filion 2012). It is likely in the best interest of governments to reduce fresh water consumption and protect fresh water sources as well as to reduce the high energy consumption associated with acquiring, treating and distributing drinking water. With the growing trend in water conservation likely to become more of a necessity, it is important to
provide support to municipalities who are transitioning to demand-side management practices.

The following review discusses two themes that are carried throughout this thesis:

1. The relationship between the quantity of water consumed by end-users and the pumping energy requirements of the water distribution system (WDS), and;
2. How frameworks are developed to facilitate the integration of water conservation objectives into the planning process for operating municipal WDSs.

2.2 The Relationship between Energy Use and Water Use and Conservation

The relationship between energy use and water conservation is explained through network hydraulics and WDS design. Systems require hydraulic capacity to meet network demand in the form of reservoirs, tanks and mechanical energy added through pumps. Consider the energy inputs needed to pump water through the system: mechanical energy is required from pumps to overcome friction losses, to meet the residual pressure requirements at network nodes such as fire flow, to supply water to end-users, and to compensate for water lost through leaky pipes or unbilled usage (leaks are ‘unaccounted-for’ water that still require pumping energy to the point at which it exits the system and can be compared to a non-revenue demand). The mechanical energy provided to the system to distribute water within the system, known as brake horsepower, can be defined for each pump as

\[ bhp = \frac{Q \cdot H \cdot \gamma}{\eta} \]  

(1)

where \( bhp \) is the brake horsepower in kW; \( Q \) is the volumetric flow through the pump in \( \text{m}^3/\text{s} \); \( H \) is the total head in m; \( \gamma \) is the specific gravity of water, in kN/m\(^3\) and; \( \eta \) is the pump efficiency,
as a percentage. Brake horsepower can therefore be used to quantify the rate of energy input into a specific system based on data collected (or simulated) from a network’s pumps.

The general water distribution network design and planning framework is outlined below. The objective of water distribution network design is to size and locate system components such as pipes, pumps, and tanks that minimize upgrade and operation costs while meeting design constraints. These constraints can include minimum pressure and hydraulic constraints such as fire flow requirements and maximum water age, and design/dimensionality constraints such as available pipe sizes and network configurations. Additional physical constraints of continuity at network junctions (2) and conservation of energy around network loops (3) are usually satisfied externally with a network solver.

**Continuity at network nodes**

\[ \sum Q_{in} - \sum Q_{out} = D_i \]  

(2)

for \( i = 1, 2, ..., N \) where \( Q_{in} \) and \( Q_{out} \) are the flows into and out of each junction in \( \text{m}^3/\text{s} \), respectively, and; \( D_i \) is the demand at each node \( i \) in \( \text{m}^3/\text{s} \).

**Conservation of energy around network loops**

\[ \sum h_f - \sum E_p = 0 \]  

(3)

for all loops where \( h_f \) is the frictional headloss through each pipe in m, and; \( E_p \) is the pumping energy added to the system in m. The frictional headloss can be defined by a commonly used equation known as the Hazen-Williams equation, which states that
where \( h_f \) is the frictional headloss in the pipe in m; \( L \) is the length of the pipe segment in m; \( Q \) is the volumetric flow through the pipe in m\(^3\)/s; \( C \) is the unitless Hazen-Williams roughness coefficient, and; \( D \) is the inner diameter of the pipe in m. Equations (2)-(4) can be solved with a network solver such as EPANET2 (Rossman 2000). The solver allows for flow and head data from the pump to be collected and used to calculate brake horsepower in equation (1).

### 2.3 Water Conservation End-Use Models

One objective of this research is to understand the water and energy savings associated with water conservation measures. It is thus necessary to quantify the water savings associated with each type of fixture or appliance upgrade being considered. The “bottoms-up” approach allows an individual household’s consumption to be modeled and to be adjusted for factors such as number of residents, typical fixtures, and water use habits. A review of previously developed end-use models for household water conserving devices is given below.

Walski et al. (1985) conducted one of the first studies to model water conservation. An algorithm was developed to calculate the effectiveness of water conservation measures using parameters to quantify the unrestricted water use, the potential water use reduction for each measure, the fraction of coverage for each measure, and the interaction between measures. The work is considered foundational to water conservation modeling. Jacobs and Haarhoff (2004) described a detailed end-use model that calculated indoor and outdoor water demand, hot water demand, wastewater flow and total dissolved solids in wastewater flow for household. The model uses
input parameters such as frequency of use, water volume, and household statistics for each end-use (toilets, basins, showers, etc.). Jacobs and Haarhoff (2007) later used elasticity and sensitivity calculations for the aforementioned parameters in an effort to remove redundancy in the model. The results found that, for indoor water demand, household size has the most significant effect on end-use demand followed by toilet flush frequency, leak volume, shower volume, and toilet volume. Aside from household size, the parameters indicate that changes in behaviors and fixture upgrades can reduce overall water demand significantly. Rosenberg (2007) used probabilistic estimation to measure the effectiveness of water conservation efforts by assigning a probability density curve to uncertain parameters falling into the categories of behavioral, technological, geographic, and demographic. The model was applied to long-term water conservation measures such as toilets, faucets, showerheads, and rainfall harvesting for Amman, Jordan and studied the feasibility of meeting conservation objectives for each measure. This work was adapted to develop water conservation equations presented later in Chapter 3. Blokker et al. (2010) simulated household water-use using a stochastic end-use model that used household statistical data. The frequency (day^{-1}), duration (s), and intensity (L/s) were estimated through surveys and described by PDFs for fixtures such as showers, toilets, washing machines, dishwashers, and taps. The output from the simulation is a single day water demand pattern for an average household. The outcome agreed with measured water demand patterns. The parameters were based on household survey data and can therefore be used without flow measurements to estimate water demand patterns. (Blokker et al. 2010)

The end-use model adopted for this study was adapted from the Rosenberg (2007) model without considering stochastic parameters. In doing so, the author simplified to process and reduced the input data necessary for a utility with limited resources and/or data collection capability.
2.4 Review of Models to Analyze Energy Use in WDS Operations

Previous research has focused on quantifying resource consumption linked to water system operation since it is often the most significant life-cycle stage of WDSs (manufacturing, operation, and disposal) in terms of both energy use and emissions, offering the most room to improve long-term environmental and economic objectives (Sahely and Kennedy 2007). Also, operational data on electricity use and water consumption are generated by the water utility and thus much easier to collect and aggregate. The work in this thesis focusses on the mechanical energy required from pumps to distribute drinking water in municipal WDSs. The significance of spatial distribution of network components on pumping energy requirements is explored. This builds on a body of work that studied the relationship between water distribution or water consumption and pumping energy requirements.

deMonsabert and Liner (1998) were the first to integrate water and energy conservation modeling using WATERGY, which quantified the energy savings that can be achieved through water conservation such as low-flow plumbing fixtures and appliances. WATERGY was developed as part of an energy conservation program and could be used to calculate operational savings for both the homeowner and the utility. Pelli and Hitz (2000) developed two indicators – structure and quality – to assess how efficiently a water utility uses energy. The structure indicator considers how spatial distribution influences energy use, which is used to derive the quality indicator. The quality indicator is the equivalent of the efficiency of energy use for a water utility. The indicators were applied to three utilities, with final overarching recommendations for thoughtful consideration of reservoir elevation as well as the large importance of proper maintenance and operation. Colombo and Karney (2005) studied the impact of leaks on the pumping energy requirements of a system with storage. The study used
the Walski et al. (1987) Anytown network and EPANET2 and pointed to the spatial distribution of network components (pumps, tanks, leaks, and demand nodes) as having an effect on the quantity of water lost through leaks as well as the overall energy use. Colombo and Karney (2005) concluded that the most important factor contributing to the relationship between leakage and energy was pipe friction, where a simulation of a deteriorated network (high friction) versus a rehabilitated network (low friction) clearly showed that the deteriorated network consumed substantially more energy for the same conditions. Arpke and Hutzler (2006) found that water use and consumption within four buildings – an apartment building, a college dormitory, a motel, and an office building – to have a significantly larger impact on resource consumption than the treatment (water and wastewater) stages of WDSs. The water consumption model is based on daily use demand patterns for fixtures and appliances within each building type. Stokes and Horvath (2006) performed life cycle energy analysis (LCEA) for three alternate water sources – recycling, importing and desalinating – in California. Their results found that the operational phase of all the system alternatives dominated energy use, followed by maintenance. Filion (2008) studied the relationship between urban form – the configuration network pipes and the distribution of end-users – and energy requirements of the network. The study noted that physical characteristics of cities, such as the existing urban form of the city itself and the dependence of water infrastructure rehabilitation schedules on other municipal infrastructure plans, means that design based on the urban form of water networks is often not realistic. It was also noted that real networks consist of pipes of a variety of materials, sizes, and ages that will affect the energy use of the network (Filion 2008). Cabrera et al. (2010) developed an energy audit to calculate the energy inputs and outputs of a water distribution system, proposing indicators that can measure the efficiency of the system in different scenarios. The model
requires a water balance as an initial input. Ghimire and Barkdoll (2010) used a sensitivity analysis to study how water demand, tank parameters, and pumping stations affect energy savings. A study of seven systems showed demand to have the highest impact on energy savings finding that, on average, a 20% reduction in demand could produce a 13% savings in energy use, and a 50% reduction resulted in a 47% savings. Herstein et al. (2011) performed an EIO-LCA multi-objective optimization of WDSs, minimizing capital costs, annual pumping energy, and environmental impacts. Pumping energy requirements dominated the environmental index (as compared to pipe and tank manufacturing) and showed a linear relationship, indicating that minimizing pumping energy requirements would also reduce environmental impacts.

The research papers reviewed all have the objective to reduce resource consumption in WDSs by establishing a relationship between water demand and pumping energy requirements of a network. The work contained in this thesis builds on these works by:

1. The inclusion of a localized geographic assessment of the energy savings within a single WDS.

2. Using a simplified end-use water use model to quantify potential energy savings in residential zones.

2.5 Review of Research that has Examined Energy Savings associated with Water Conservation Measures

A number of papers discuss collaborations between researchers and municipalities that sought to reduce water use and associated environmental burdens through network case studies and policy recommendations. Many of the papers have an objective to quantify environmental burdens
(GHG emissions, energy use, water use, etc.) for use in policy making and/or WDS operations for municipal utilities.

Lundie et al. (2005) performed a life-cycle assessment study for Sydney Water in Australia that considered various scenarios to assess if further measures (demand management, increasing energy efficiency, energy generation from biosolids, desalination, and upgrades to sewage treatment plants) would increase the sustainability of Sydney’s urban water system on the basis of total water and energy use, global warming potential, eutrophication, and toxicity levels. The study also implemented a greenfield model as an alternative to traditional water and wastewater delivery for a new suburb, noting savings for water and energy use as well as significant environmental impact reduction. From the study, Lundie et al. (2005) drew attention to the substantial pumping energy requirements to transport water and wastewater to fringe suburbs. Sahely and Kennedy (2007) used environmental indicators such as GHG emissions (on-site and upstream), chemical use, electricity use, treated wastewater and also water demand and distribution losses to perform a scenario analysis for the operational phase of the City of Toronto’s urban water system. The study used the indicators to compare pipe renewal, sewer relining, demand management strategies, and energy recovery. Demand management was the most favorable scenario with the results showing that a reduction in demand by 15% could result in 12-18% savings for all the indicators considered in the study. The results indicated that demand management had the lowest environmental burden while also being one of the most cost-effective options owing to the significant cost savings from reduced energy and chemical use. Racoviceanu and Karney (2010) used an LCA for the City of Toronto residential sector to quantify the operational energy use, GHG emissions and embodied burdens along with water savings from new low-flow fixtures and appliances and implementing rainwater harvesting. The
results were heavily influenced by whether or not water heating was included in the assessment, highlighting the importance of boundary selection in LCAs because of the high energy requirements to heat water. Both the water efficiency and rainwater scenarios showed significant annual energy, water, and GHG savings when water heating was included. Stokes and Horvath (2011) developed the Water-Energy Sustainability Tool (WEST) to identify and quantify material and energy inputs and material and environmental outputs associated with the construction and operation of urban water systems. WEST estimates the global warming effects (GWE) associated with material production and delivery, equipment use, energy production, and sludge disposal. A case study of a Northern California utility showed that for all life-cycle activities, 50% of the GWE were due to energy production. Of the life-cycle stages, operation contributed the most to GWE (67%). Schulz et al. (2011) partnered with four utilities in Melbourne, Australia and developed a streamlined tool called the Environmental Sustainability Assessment Tool (ESAT) to reduce the complexity of sustainability assessments. The tool evaluates economic and environmental performances and the study showcased a case-study for a development outside of the city center of Melbourne using scenario analysis to compare the simplified assessment to LCA and life cycle costing. The simplified ESAT model was able to perform similarly to standard LCA and LCC methods and met its purpose of reducing the time and resources necessary to aid in the decision making process. Burn et al. (2002) examined the impact of demand management and changes in system operations on the cost of potable water pipe networks. They found that demand management could save 25-45% of related costs and that pressure management could further reduce costs by 20-55%.
The work present in this thesis provides a methodology for utilities who do not necessarily have the data collection systems or financial capability to perform large-scale studies of their networks but who wish to engage in water conservation planning. The thesis’ unique contributions are:

1. Developing a planning framework for municipal utilities to prioritize water conservation programs and campaigns based on geographic location.
2. Using socio-economic and demographic factors to calculate feasible water savings for each residential zone within a municipality.
3. Examining the relationship between energy requirements and geographic location for various water conservation levels using relative water and energy indicators.
4. Reducing the input data and time intensity of water conservation planning studies.

2.6 Summary

The above works highlight contributions to reducing energy requirements for WDSs as well as the development of planning frameworks to help municipal utilities reduce their resource consumption. Of great significance is the ability of the research to guide new policy recommendations for water conservation planning. An objective of this thesis is to provide a specific set of recommendations with regard to prioritizing water conservation plans based on socio-economic and demographic factors and the geographic dependence of potential water and energy savings. There could also be potential to use the framework in long-term decision making with regard to system upgrades and land-use planning by identifying regions within a network that consume relatively more energy. The discussions above identified two major areas of research which contribute to the thesis objectives: quantifying energy used to move water
through WDSs, and developing planning frameworks to reduce operational resource consumption of WDSs.

2.7 References


CHAPTER 3

Quantifying the mechanical energy response to localized water conservation

3.1 Abstract

Water conservation does not necessarily produce energy savings equally throughout a network. Factors that determine energy savings within the network include the location of reduced nodal demands relative to major components such as water treatment plants, pumping stations, elevated tanks, and the pipe roughness and size of water mains that convey flows to different network nodes. This research presents a new methodology to quantify the potential water and energy savings associated with implementing various water conservation measures within a water distribution network. The methodology categorizes small, semi-homogeneous neighbourhoods based on homeownership and residential land-use to specifically target smaller areas for water conservation. A water conservation plan is tailored to each defined area. Energy intensity and energy elasticity indicators are developed to assess the mechanical energy used in the network to distribute water to end-users. A case study from Kingston, Ontario is presented. For marginal water savings, the energy response is inelastic to changes in water demand. The low energy elasticity explained why the energy intensity of the network increased in response to reduced water demand.
3.2 Introduction

The state of North American drinking water infrastructure has reached a decisive moment for municipalities and water utilities. Aging drinking water infrastructure has resulted in real water losses of 20-50% between the source and the consumer’s tap (Brothers 2001), and increased the pumping energy requirements of networks (Colombo and Karney 2005). The importance of safe and reliable water supply means that it is crucial to develop long-term solutions that make provisions to protect fresh water resources. It has been argued that standard supply-side management – increasing drinking water infrastructure capacity and increasing available fresh water resources – often does not focus enough attention on long-term solutions for drinking water infrastructure planning and management (Brothers 2001). Demand-side management can be described as any action that decreases water demand, such as reducing leakage rates, peak shaving, and water conservation. Examples such as reducing potable water demand by instilling attitudinal changes, installing low-flow fixtures/appliances, rainwater harvesting, greywater reuse, lowering leakage rates, and shifting use to off-peak periods produce a smaller environmental burden, can be economically profitable and are often readily implemented (Racoviceanu and Karney 2010).

Water conservation does not necessarily produce energy savings equally throughout a network. Factors that determine energy savings within the network include the location of reduced nodal demands relative to major components such as water treatment plants, pumping stations, elevated tanks, and the pipe roughness and size of water mains that convey flows to different network nodes. Filion (2008) considered the impact of urban form, the configuration of network pipes and the distribution of end-users, on energy requirements of networks. It was noted that factors such as pipe characteristics and the dependence of WDS rehabilitation schedules on other municipal
infrastructure plans, along with shifting urban forms, cause networks to differ substantially in their energy use. Since drinking water mains are typically replaced at the time of road reconstruction, efforts that focus on no-dig, above ground approaches to water and energy conservation can be considered a valuable approach to reducing pumping energy. The effectiveness of water conservation efforts often turn on factors such as end-user participation or adoption rates, savings from fixtures and/or appliances, and behavioural changes associated with different conservation measures (Rosenberg 2007). Because of their limited financial resources, municipalities have difficulty promoting and monitoring the adoption and effectiveness of water conservation efforts at the end-user level. These obstacles also make it difficult to estimate city-wide benefits.

Given this, the methodology presented in this chapter categorizes small, semi-homogeneous neighbourhoods based on household demographics to specifically target smaller areas for water conservation. A water conservation plan is tailored to each defined area by specifying which conservation measures are feasible to implement, desired by the customer, and are attractive to the utility based on a potential return on investment in the form of reduced electricity bills to pump and treat water. The planning methodology provides information on savings in water use achievable in different geographic regions where water conservation measures are implemented. This information allows a water utility to prioritize where to invest its resources to implement water conservation measures in an urban area.

3.3 Water-Energy Nexus For Water Distribution Systems

Previous studies have examined the relationship between water conservation initiatives and the pumping energy saved from a reduction in demand. The studies reviewed below have examined the following two themes: (i) the relationship between water conservation efforts and energy
savings, and (ii) the development of planning frameworks to help municipalities and water utilities reduce their water and energy use.

deMonsabert and Liner (1998) integrated water and energy conservation modeling using WATERGY to quantify the energy savings that can be achieved through water conservation such as low-flow plumbing fixtures and appliances. WATERGY was the first of its kind in computational water conservation modeling and was part of an energy conservation program to calculate operational savings for homeowners and utilities. Lundie et al. (2005) performed a life-cycle assessment of Sydney Water’s strategic planning document WaterPlan 21. The study performed scenario analysis to assess if further measures (demand management, increasing energy efficiency, energy generation from biosolids, supply augmentation (desalination) and upgrades to sewage treatment plants) would decrease the environmental burden of Sydney’s urban water system (Lundie et al. 2005). Lundie et al. (2005) drew attention to the substantial pumping energy requirements to transport water and wastewater to fringe suburbs. Colombo and Karney (2005) studied the impact of leaks on the pumping energy requirements of a system with storage using the Walski et al. (1987) Anytown network. Colombo and Karney (2005) noted that the spatial distribution of network components (pumps, tanks, leaks, and demand nodes) had an effect on the quantity of water lost through leaks as well as the overall energy use, but concluded that the most important factor contributing to the relationship between leakage and energy was pipe friction. A simulation of a deteriorated network (high friction) versus a rehabilitated network (low friction) clearly showed that the deteriorated network consumed substantially more energy for the same conditions (Colombo and Karney 2005). Sahely and Kennedy (2007) used environmental indicators such as GHG emissions (on-site and upstream), chemical use, electricity use, treated wastewater and also water demand and distribution losses to perform a
scenario analysis for operational phase of the City of Toronto’s urban water system. The results showed that demand management was one of the most cost-effective owing to the significant cost savings from reduced energy and chemical use (Sahely and Kennedy 2007). Ghimire and Barkdoll (2010) used a sensitivity analysis to study how water demand, tank parameters, and pumping stations affect system energy use. A study of seven systems showed demand to have the highest impact on energy savings finding that, on average, a 20% reduction in demand could produce a 13% savings in energy use, and a 50% reduction resulted in a 47% savings. The study was conducted on relatively small systems and further investigation would be needed to draw conclusions for large systems. Racoviceanu and Karney (2010) used a life-cycle analysis for the City of Toronto residential sector to quantify the operational energy use, GHG emissions and embodied burdens along with water savings of a new low-flow fixtures and appliances and implementing rainwater harvesting. The study noted that boundary selection in life-cycle analyses heavily influences what environmental inputs and outputs are counted in the analysis (Racoviceanu and Karney 2010).

Although previous works have noted the importance of pipe age, leakage rates, the spatial distribution of network components, and the nodal distribution on pumping energy requirements, no prior study has quantified the relationship between energy use and the geographic location of water conservation efforts in a distribution network. The results of this study are presented in a manner that allows practitioners to familiarize themselves with the network characteristics that are most influential on their networks’ energy use and to prioritize water and energy conservation strategies based on this information. The objectives of this paper are to: (i) present a new water conservation planning framework that prioritizes geographic locations based on the energy savings within the network; (ii) incorporate household socio-economic factors into water
conservation planning, and; (iii) develop a set of indicators that are used to assess a network’s conservation strategies based on water and energy savings. The planning framework developed was used to identify feasible water conservation measures by location and socio-economic areas for the City of Kingston. A major contribution of this research is the development of a planning tool that uses household, demographic factors, and land-use data to build a geographically-targeted water conservation plan for a real water distribution system. The work provides a methodology for utilities who do not necessarily have the data collection systems or financial capability to perform large-scale studies of their networks but who wish to engage in water or energy conservation planning.

The chapter is structured as follows. The conceptual water conservation planning framework is explained by presenting a water savings model, a pumping energy model, and network indicators for energy and water use. The framework is then applied to the City of Kingston’s drinking water supply system. The water conservation scenarios presented in the case study are selected based on housing demographics for Kingston. The conclusions offer broader implications of conducting a geographically-targeted assessment of water conservation programs and the related pumping energy requirements.

3.4 Methodology

3.4.1 Overview of Framework

In this thesis, potential savings, represented as a percent reduction, are calculated on a fixture-by-fixture basis. For example, this can include installing low-flow toilets and faucets in rental units or selling efficient dishwashers and laundry machines to homeowners. An adoption rate is
chosen for each program, i.e. the number of households or storeowners who will participate, and can be based on either a target set by the municipality, or by an assumed limit of potential end-users who would participate. Using a network model that simulates an average daily demand (ADD), the percent savings are applied to demand nodes within each area and a network model simulation is performed. From the model simulation, the necessary data is extracted to calculate the associated energy savings. In summary, the steps of the methodology are:

1. Define the targeted demographic areas within the limits of the distribution network to establish water conservation target areas.
2. Develop a list of feasible conservation measures for each area identified in Step 1.
3. Use water end-use model (discussed in 3.4.2) to predict the water conservation savings for the selected measures within each area as compared to the baseline scenario.
4. Run hydraulic model simulations for chosen demand scenarios in Step 3 to quantify the energy use savings associated with each water conservation plan and area.
5. Calculate the system indicators (discussed in 3.4.4) to compare the areas on the basis of energy and water savings.

### 3.4.2 Water Conservation End-Use Model

Water conservation end-use models consider the water savings potential for the replacement of old high-volume and high-flow fixtures or appliances with new water-efficient devices in households. For instance, US households built prior to the Environmental Protection Agency (EPA) Act of 1992, wherein 6L toilets became mandatory for all new household toilets, are likely to have toilets that use up to 20L/flush. By installing new 6 L/flush toilets, a 3-person
home could save upwards of 34% of their water use per year (EPA 2012). The total savings in an area is found by multiplying the average household savings by the number of participating customers. This approach is best suited for homogenous neighbourhoods, where planners can assume similar levels of current water use and projected water savings in each household. However, when these results are ‘blanketed’ across municipalities the assumption of homogenous savings becomes less reliable. Estimating household uptake rates for rebate programs becomes difficult – factors such as income, homeownership, and awareness can dictate a household’s ability or willingness to participate in water conservation programs. Some research has dealt with this issue by using probabilistic analysis of water conservation. Rosenberg (2007) used probabilistic estimation to measure the effectiveness of water conservation efforts by assigning a probability density curve to uncertain parameters falling into the categories of behavioral, technological, geographic and demographic. The model was applied to long-term water conservation measures such as toilets, faucets, showerheads, and rainfall harvesting for Amman, Jordan and studied the feasibility of meeting conservation objectives for each measure. Blokker et al. (2010) simulated household water-use using a stochastic end-use model that used household statistical data. The frequency (day\(^{-1}\)), duration (s), and intensity (L/s) were estimated through the survey and described by PDFs for fixtures such as showers, toilets, washing machines, dishwashers, and taps. The output from the simulation is a one-day water demand pattern for an average household. The outcome agreed with measured water demand patterns. For this thesis, the author identifies socio-economic drivers for water conservation for and uses adoption rates determined through consultation with the utility. Potential water conservation devices are selected for each neighbourhood that match socio-economic group with suitable and desirable conservation measures.
In this thesis, the water end-use model in equations (1)-(5) of Rosenberg (2007) was adapted to quantify household water savings. The equations are based on specifications for new and old water consuming-devices as well as typical consumer behaviour. Table 3.1 outlines the variables used in equations (1)-(5). The water savings, $Δq$, are given on a per year basis.

\[
\begin{align*}
Δq_{\text{shower}} &= \frac{52}{1,000} (Q_{\text{existing}} - Q_{\text{retrofit}})_{\text{shower}} \times B \times F \times G \\
Δq_{\text{bath faucet}} &= \frac{1,000}{365} (Q_{\text{existing}} - Q_{\text{retrofit}})_{\text{faucet}} \times M \times B \\
Δq_{kitchen faucet} &= \frac{1,000}{365} (Q_{\text{existing}} - Q_{\text{retrofit}})_{\text{faucet}} \times O \\
Δq_{\text{toilet}} &= \frac{1,000}{52} (Q_{\text{existing}} - Q_{\text{retrofit}})_{\text{toilet}} \times U \times B \\
Δq_{\text{laundry}} &= \frac{1,000}{1,000} (Q_{\text{existing}} - Q_{\text{retrofit}})_{\text{laundry}} \times W \times B
\end{align*}
\]

The sum of equations (1)-(5) produces a typical average indoor daily demand for a single household.

Table 3.1: Parameters for calculating total end-user demand

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>Household size</td>
</tr>
<tr>
<td>$F$</td>
<td>Length of shower</td>
</tr>
<tr>
<td>$G$</td>
<td>Shower frequency</td>
</tr>
<tr>
<td>$M$</td>
<td>Faucet use (bathroom)</td>
</tr>
<tr>
<td>$O$</td>
<td>Faucet use (kitchen)</td>
</tr>
<tr>
<td>$Q_{existing}, Q_{retrofit}$</td>
<td>Existing or retrofitted flow rate of fixture/appliance</td>
</tr>
<tr>
<td>$U$</td>
<td>Toilet flush frequency</td>
</tr>
<tr>
<td>$W$</td>
<td>Laundry load frequency</td>
</tr>
</tbody>
</table>

3.4.3 Pumping Energy Requirements

To meet residual pressure requirements at demand nodes, almost all networks require added hydraulic lift to pump water to higher elevations and to overcome frictional losses in the system.
In order to account for all energy entering and leaving the network, an energy balance is done on a defined control volume. Cabrera et al. (2010) developed an energy audit to calculate the energy inputs and outputs of a water distribution system. As shown in Figure 3.1, pumps, reservoirs and tanks are considered external inputs of energy to the control volume while nodal demands, frictional losses and leaks are considered energy outputs, seen in equation (6).

![Figure 3.1: Control volume with network components in energy balance](image)

Table 3.2 defines the terms in equation (6) where $\dot{W}_{P,t}$ is the rate of work at time $t$, $Q_{i,t}$ is the volumetric flow through the specific network component $i$ at time $t$ in $m^3/s$; $Q_{j,t}$ is the volumetric flow through pipe $j$ at time $t$ in $m^3/s$; $H_{i,t}$ is the total head at component $i$ at time $t$ in m; $h_{j,t}$ is the headloss through pipe $j$ at time $t$ in m; $\gamma$ is the specific gravity of water in kN/m$^3$; $\Delta t$ is the time step, and; $\eta_i$ is the pump efficiency, as a percentage.

$$[E_P + E_R]_{in} - [E_N - E_F]_{out} = 0$$  \hspace{1cm} (6)
Table 3.2 Instantaneous rate of work and numerical integration terms for energy balance

<table>
<thead>
<tr>
<th>Energy supplied by pumps</th>
<th>Instantaneous, time $t$</th>
<th>$\dot{W}<em>{P,t} = \gamma \cdot \sum</em>{i=1}^{p} \frac{Q_{Fi,t} \cdot H_{i,t}}{\eta}$</th>
<th>$E_P = \dot{W}<em>P = \sum</em>{t=0}^{T} (\dot{W}<em>{P,t} + \dot{W}</em>{P,t+\Delta t}) \cdot \frac{\Delta t}{2}$ (7)-(8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy supplied by tanks and reservoirs</td>
<td>$\dot{W}<em>{R,t} = \gamma \cdot \sum</em>{i=1}^{r} Q_{Ri,t} \cdot H_{i,t}$</td>
<td>$E_R = \dot{W}<em>R = \sum</em>{t=0}^{T} (\dot{W}<em>{R,t} + \dot{W}</em>{R,t+\Delta t}) \cdot \frac{\Delta t}{2}$ (9)-(10)</td>
<td></td>
</tr>
<tr>
<td>Energy consumed by friction in pipes</td>
<td>$\dot{W}<em>{F,t} = \gamma \cdot \sum</em>{j=1}^{l} Q_{Fj,t} \cdot h_{j,t}$</td>
<td>$E_F = \dot{W}<em>F = \sum</em>{t=0}^{T} (\dot{W}<em>{F,t} + \dot{W}</em>{F,t+\Delta t}) \cdot \frac{\Delta t}{2}$ (11)-(12)</td>
<td></td>
</tr>
<tr>
<td>Energy consumed by nodes and leaks</td>
<td>$\dot{W}<em>{N,t} = \gamma \cdot \sum</em>{i=1}^{n} Q_{Ni,t} \cdot H_{i,t}$</td>
<td>$E_N = \dot{W}<em>N = \sum</em>{t=0}^{T} (\dot{W}<em>{N,t} + \dot{W}</em>{N,t+\Delta t}) \cdot \frac{\Delta t}{2}$ (13)-(14)</td>
<td></td>
</tr>
</tbody>
</table>

Over the long-term, the energy supplied by tanks and reservoirs becomes negligible in comparison to the energy supplied by pumps. Constant fluctuations of flow into and out of the tanks (from diurnal filling and draining) result in an overall energy contribution with a near-zero average. Also, although friction losses can be quantified by network models, the values are not needed as this energy is reflected in the total energy supplied by the pumps (and the reservoirs or tanks in the short term). Since this study considers average daily demand over a long-term simulation, the only numerical integration necessary for the analysis is that of the pumps. The energy leaving through the nodes is considered the useful energy that is delivered to the end-user, and is reflected in the water demand calculations discussed next in the section 3.4.4. Therefore, the following discussion considers the total energy required to pump water through the pumps and the useful energy that reaches the end-user in the form of daily water demand.
3.4.4 Energy and Water Indicators

A number of definitions and indicators are developed by the author to assess the mechanical energy used in the network to distribute water to end-users. The definitions and indicators are defined below.

Energy Efficiency (EE): the ratio between the useful energy (i.e. the energy ‘contained’ in the water delivered the end-users) and the overall energy input into the system by the pumps. EE is the percentage of energy that is not wasted by physical losses through leaks, non-revenue water, and frictional losses in the network components. EE is reflected in this model as the water delivered to end-users.

Energy Intensity (EI): the total pumping energy used per unit of water delivered. The EI of a network is defined as the amount of kilowatt-hours required to deliver one cubic metre of water (kWh/m³). If a water utility reduces the EI of their network by upgrading their network components (new pumps, pipes, etc.), processes (treatment facilities, pump operations, etc.) or overall service delivery (supply- and demand-side management of water and/or energy), they have increased their energy efficiency (EE).

Energy Elasticity (e): measures how much a change in total end-user water demand affects pumping energy, relative to the ‘do-nothing’ base case scenario. Mathematically, it is the ratio of the percentage change in pumping energy to the percentage change in water demand. If e > 1, the energy efficiency of the network has improved because the pumping energy requirement decreases by a greater factor than the water demand decreases (resulting in a lower value of EI). Otherwise if e < 1, the energy efficiency of the network has decreased whereby a decrease in
water demand produces an increase in energy intensity. If $0 < e < 1$, although the energy efficiency decreases, a one percent water savings produces $e$ percent in energy savings.

*Water Savings Indicator*

The water savings indicator is used to measure the percentage change in water demand in the network owing to the application of water conservation measures to a specific area of the network. The water savings indicator is written as

$$\%Q_x = \frac{Q_b - Q_x}{Q_b} \%$$  \hspace{1cm} (7)

where $Q_b$ is the base case average daily water demand (no conservation) and $Q_x$ is the water consumption for the entire network after water savings were applied to area $x$.

*Energy Savings Indicator*

The energy savings indicator is used to measure the percentage change in pumping energy use in the network owing to the application of water conservation measures to a specific area of the network. The water savings indicator is written as

$$\%E_x = \frac{E_b - E_x}{E_b} \%$$  \hspace{1cm} (8)

where $E_b$ is the base case energy use (‘do-nothing’) and $E_x$ is the energy use for the entire network due to changes in water demand in area $x$.

*Energy Intensity Indicator*

The energy intensity (EI) indicator measures the amount of energy used to distribute a unit volume of water *in the entire network*. The energy intensity indicator is used in this paper to characterize the change in energy efficiency that results from the implementation of a water
conservation initiative(s) in a specific neighborhood or area of a water distribution network. EI is a ‘snapshot’ of the entire network’s energy response to water conservation efforts in a localised area. Therefore, the EI indicates how changes to water demand in a specific neighbourhood effect the energy efficiency (EE) of the entire network. The EI indicator is defined as

$$EI_x = \frac{E_x}{Q_x}$$

where $EI$ is the energy intensity (measured in kWh/m$^3$) that corresponds to changes in demand (from water conservation) in area $x$; $E$ is the total energy used by all pumps in the network after water conservation initiative(s) have been implemented in area $x$ (kWh), and; $Q$ is the total demand in the network after water conservation initiative(s) have been implemented in area $x$, in m$^3$. For example, if reducing water demand in one designated area results in an EI value lower than the value corresponding to the base case, the water demand initiative in the designated area has increased the overall EE of the network. Conversely, if the EI value increased, more energy was spent on each cubic meter of water distributed across the entire network, indicating an overall decrease in EE for the network.

**Energy Elasticity Indicator**

The energy elasticity indicator describes how the system has responded to change in water demand (from water conservation) relative to the base case. It represents the ratio of the percentage change in pumping energy use to the percentage change in demand across the entire network owing to the application of water conservation measures to a specific area of the network. Energy elasticity is described mathematically by
where \( e \) is the energy elasticity (unitless); \( \%E_x \) is the percentage change of pumping energy use due to a reduction in water demand in the network owing to water conservation measures in area \( x \), and; \( \%Q_x \) is the percentage change in average daily demand across the entire network owing to a demand reduction (from water conservation) in area \( x \).

By definition, energy elasticity tells us how many percentage points pumping energy changes in response to one percentage point change in water demand. A positive value of energy elasticity greater than 1 indicates an energy saving and an increase in energy efficiency due to a decrease in water demand. A positive value of energy elasticity less than 1 indicates overall energy savings but a decrease in energy efficiency. A negative energy elasticity indicates an increase in energy use and a decrease in energy efficiency due to a decrease in water demand.

3.5 Case Study

Kingston Township and Pittsburgh Township amalgamated in 1998 to form what is now the City of Kingston. The Kingston Drinking Water Supply System is owned by the City of Kingston and operated by Utilities Kingston, a private utility that takes direction from City Council. The system limits are, in general, south of Highway 401 and north of the St. Lawrence River and Lake Ontario, spanning approximately 20km from Coronation Boulevard in the west end to the Milton subdivision on the east side of County Road 2 (UK 2010). A full map of the City of Kingston is included in Appendix A, Figure A.1.
The full system consists of two hydraulically separate systems. The distribution systems are illustrated in Appendix A, Figure A.1 and Figure A.2 and are referred to as Kingston West, Kingston Central, and Kingston East. Kingston Central and East function together as one system connected by the James Street Booster Station. Kingston West is hydraulically connected to the Central system only in emergency cases. The downtown core located in Kingston Central contains the oldest pipes in the network and has also been the focus of much pipe repair and replacement in recent years. Kingston West is comprised mostly of residential neighbourhoods with relatively new suburbs to the north serviced by relatively new water mains, and established neighbourhoods along the water. Kingston Central has a mix of residential, commercial and institutional land-uses. The residential demographic includes neighbourhoods independently dedicated to students, homeowners, and renters. Kingston East is mostly a residential area of homeowners, aside from the Canadian Forces Base (CFB) Kingston and the Royal Military College.

The system is serviced by two Water Treatment Plants. Point Pleasant Water Treatment Plant services Kingston West and King Street Water Treatment Plant services Kingston Central and Kingston East. The system comprises over 540 km of water mains, 2 reservoirs/pumping stations, 6 elevated tanks, 5 booster stations, over 4,750 km of main line valves and 3,000 fire hydrants (UK 2010). The case study presented focuses only on Kingston Central and Kingston East. Below in Table 3.3 is a description of the network components located in Kingston Central and East, as depicted in Appendix A, Figure A.2. The Kingston WDS all-pipes network model can also be found in Appendix A, Figures A.3 to A.5, indicating the network’s pipe sizes, pipe materials, and demand node elevations.
Table 3.3 City of Kingston Central and East water distribution network components

<table>
<thead>
<tr>
<th>Network Component</th>
<th>Description (Utilities Kingston 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kingston Central water supply and distribution system</strong></td>
<td>Operates as one pressure zone with one water treatment plant, an elevated tank (Tower Street) and a reservoir with a booster station (Third Ave. reservoir/pump station)</td>
</tr>
</tbody>
</table>
| Kingston Central Water Purification Plant | Seven pumps with a theoretical firm pumping capacity of 133.6 ML/day  
Two pumps are activated during ADD simulations in the network model |
| Tower Street Elevated Tank | Water level at Tower Street is primary control for high-lift pump operations at the WPP and James Street BS  
Total volume of 3.4 ML and a functional volume of 1.9ML |
| Third Avenue Reservoir and Booster Station | In-ground reservoir with a total volume of 23.2 ML and a functional volume of 12.8 ML  
Contains three pumps to maintain pressure in Zone 1  
The reservoir and the booster station are not active during ADD simulations in the network model |
| **Kingston East water supply and distribution system** | Connected to Kingston Central by James Street BS and operates on a different pressure zone |
| James Street Booster Station (BS) | Three pumps with a theoretical firm pumping capacity of 18.2 ML/day, average day requires only one pump  
One pump is active during ADD simulations in the network model |
| CFB (Canadian Forces Base Kingston) Elevated Tank | Water level provides primary control for James Street BS as well as water storage and pressure equalization for Kingston East  
Total volume of 2.27 ML and a functional volume of 0.73ML  
Directly influences water levels in the Gore Road and Milton Avenue standpipes |
| Gore Road Standpipe | Total volume of 1.22 ML and a functional volume of 0.16 ML, providing water storage and pressure equalization for northern area of Kingston East |
| Milton Avenue (Forrest) Standpipe | Total volume of 1.28 ML and a functional volume of 0.17 ML, providing water storage and pressure equalization for southern area of Kingston East |
3.5.1 Water Conservation Planning Approach

Step 1: Define the targeted demographic areas within the limits of the distribution network to establish water conservation target areas.

A problem often cited by municipal water infrastructure managers in implementing water conservation is that it is difficult to predict how many households will participate in the program, which leads to uncertainty in long-term planning with regard to network capacity. Understanding what drives adoption rates may help reduce this uncertainty. Babooram and Hurst (2011) surveyed Canadian households with regard to adoption rates and attitudes toward various water and energy conserving measures and to study which factors – such as age, income, education, homeownership, and dwelling age and type – drive the adoption of water- and energy-efficient devices in Canadian households. The findings suggested that home ownership, higher levels of education, and higher income increased the likelihood that a household would adopt conservation measures (Babooram and Hurst 2011). The following socio-economic categories were chosen in collaboration with a conservation officer at Utilities Kingston to best define Kingston’s residential neighbourhoods:

Homeowners: Homeowners are considered most likely to invest in pricier fixtures (laundry machines, dishwashers) for their households because they will see any savings reflected in their billing and are likely to stay in the same house for several years. However, they are also more likely to consume outdoor water for gardening, lawn watering and filling pools. It is noted that the decision to upgrade fixtures is solely the choice of the homeowners.
**Transitional Area:** A housing area that is in the midst of transitioning from rental units to home ownership and offers a slightly higher adoption rate because of the housing ‘flip’ likely to be made before a sale.

**Students:** Student households are often owned by landlords who own multiple units. If a landlord takes advantage of rebate programs, many units can be upgraded. Students are not likely to use outdoor water on a regular basis since units are often empty during the hottest months of the year.

**Rental households:** Rental households are similar to student households in that landlords often decide which fixtures to upgrade within the home. These households are less likely to upgrade large investment items such as laundry machines and dishwashers.

**Step 2:** Develop a list of feasible conservation measures for each area identified in Step 1.

The author, in partnership with Utilities Kingston’s conservation officer, identified water conservation measures that were most applicable for each of the above socio-economic categories, and were measures the utility was open to including in rebate programs. Table 3.4 summarizes the fixtures and appliances for each category.
Table 3.4 Applied water conservation plan for each demographic

<table>
<thead>
<tr>
<th>Applied water conserving devices</th>
<th>Owner</th>
<th>Student</th>
<th>Transitional</th>
<th>Rental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>Bathroom basin</td>
<td>Bathroom basin</td>
<td>Bathroom basin</td>
<td>Bathroom basin</td>
</tr>
<tr>
<td></td>
<td>Kitchen basin</td>
<td>Kitchen basin</td>
<td>Kitchen basin</td>
<td>Kitchen basin</td>
</tr>
<tr>
<td></td>
<td>Low-flush toilets</td>
<td>Low-flow showerheads</td>
<td>Low-flow showerheads</td>
<td>Low-flush toilets</td>
</tr>
<tr>
<td></td>
<td>Water efficient dishwashers</td>
<td>Low-flush toilets</td>
<td>Water efficient laundry machines</td>
<td>Low-flow showerheads</td>
</tr>
<tr>
<td></td>
<td>Water efficient laundry machines</td>
<td>Water efficient laundry machines</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Step 3: Use water end-use model to predict the water conservation savings for the selected measures within each area as compared to the baseline scenario.

The baseline water use for each household type assumed the standard water flows on a fixture-by-fixture level in Table 3.5. The conservative water use after implementing the water conservation plan from Table 3.4 was calculated using the water use for low-flow fixtures in Table 3.5. The values for the behavioural parameters that were first introduced in Table 3.1 are summarized below in Table 3.6.
Table 3.5 Typical water conserving fixtures considered as part of a water conservation plan

<table>
<thead>
<tr>
<th>Water-consuming fixture</th>
<th>Standard Water Use*</th>
<th>Conservative Water Use</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathroom basin$^2$</td>
<td>13.5</td>
<td>6</td>
<td>L/min</td>
</tr>
<tr>
<td>Kitchen basin$^2$</td>
<td>13.5</td>
<td>7.5</td>
<td>L/min</td>
</tr>
<tr>
<td>Low-flow showerhead$^2$</td>
<td>17.1</td>
<td>9.5</td>
<td>L/min</td>
</tr>
<tr>
<td>Low-flush toilet$^2$</td>
<td>19</td>
<td>5.7</td>
<td>L/flush</td>
</tr>
<tr>
<td>Laundry$^3$</td>
<td>150</td>
<td>80</td>
<td>L/load</td>
</tr>
<tr>
<td>Water efficient dishwasher$^3$</td>
<td>40</td>
<td>22</td>
<td>L/cycle</td>
</tr>
</tbody>
</table>

*On a per-fixtures basis

Table 3.6 Estimated values used for calculating total household demand

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$ Household size</td>
<td>$^3$</td>
<td>persons/HH</td>
</tr>
<tr>
<td>$F$ Length of shower</td>
<td>$^8$</td>
<td>min</td>
</tr>
<tr>
<td>$G$ Shower frequency</td>
<td>$^5$</td>
<td>#/person/week</td>
</tr>
<tr>
<td>$M$ Faucet use (bathroom)</td>
<td>$^5$</td>
<td>min/day/person</td>
</tr>
<tr>
<td>$O$ Faucet use (kitchen)</td>
<td>$5-10^4$</td>
<td>min/day</td>
</tr>
<tr>
<td>$U$ Toilet flush frequency</td>
<td>$^4$</td>
<td>#/person/day</td>
</tr>
<tr>
<td>$W$ Laundry load frequency</td>
<td>$^1$</td>
<td>#/person/week</td>
</tr>
</tbody>
</table>

$^1$StatsCan (2012)
$^2$Environment Canada (2011)
$^3$National Geographic (2012)
$^4$Author's estimate

Equations (1)-(5) were used to calculate the average baseline water use for each household type without conservation and were then used to calculate the potential water savings when low-flow fixtures were installed. The water percentage saved by implementing water conservation for each household type is summarized below in Table 3.7. The targeted adoption rates were chosen through consultation with the water conservation officer at Utilities Kingston based on the above descriptions of the four housing demographics. The savings that were used to run simulations were calculated by multiplying the potential water savings per household by the suggested adoption rate. These savings were applied to all demand nodes contained within each geographic region identified in Figure 3.2 and numbered 1 through 16. Due to the sensitive nature of
Figure 3.2: Residential water conservation planning areas for the City of Kingston
assigning a particular neighbourhood with a socio-economic status, the socio-economic designations have not been identified on the map.

Table 3.7 Water savings, adoption rates, and final water conservation savings for each socio-economic target area

<table>
<thead>
<tr>
<th>Household Type</th>
<th>Water Savings per Household</th>
<th>Targeted adoption rate</th>
<th>Savings Applied in Conservation Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>40%</td>
<td>15%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Student</td>
<td>52%</td>
<td>15%</td>
<td>7.8%</td>
</tr>
<tr>
<td>Transitional</td>
<td>46%</td>
<td>20%</td>
<td>9.2%</td>
</tr>
<tr>
<td>Rental</td>
<td>51%</td>
<td>15%</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

3.6 Results and Discussion

Step 4: Run hydraulic model simulations for chosen demand scenarios in Step 3 to quantify the energy use savings associated with each water conservation plan and area, and;

The network model used a commercial software similar to EPANET2 and a GIS interface to run the scenario simulations on the City of Kingston distribution network. EPANET2 is a computer software package that simulates the hydraulic response within water pipe networks (Rossman 2000). The user can construct an all-pipe network of their distribution system using pipes, nodes, pumps, valves, and storage that characterize their network (Rossman 2000). Water flows, tank levels, pressures, etc. are tracked throughout the network when the user performs an extended period simulation (Rossman 2000). The GIS model allows the user to use land-use planning and other geographic data to manipulate and summarize network characteristics for a chosen purpose.

The network output data consisted of 10 minute time steps over the course of 96 hours. Figure 3.3 plots one 24-hour segment of the output results for the Tower Street tank water levels and the
diurnal pattern used for the City of Kingston. Figure 3.3 demonstrates the tank drains in response to the end-use peaks at 10am and 8pm and fills during off-peak hours.

![Tower Street Head levels over one 24-hour period](image)

**Figure 3.3:** Water levels in Tower Street tank and daily diurnal pattern for one 24-hour period

Prior to calculating the total energy for the cases, the pumping schedules were corrected for inconsistencies in the on/off cycles. The network output data consisted of 10 minute time steps over the course of 120 hours. Day 1 was discarded from the data because the tanks fill during the first hours of the day, which does not accurately represent a typical day. Prior to calculating the total energy for the cases, the pumping schedules were corrected for inconsistencies in the on/off cycles. Figure 3.4 in based on the uncorrected data. For the purpose of the explanation, Scenario 8 is compared to the baseline. The black line corresponds to the difference in flow at the WTP.
for the main pump in 10 minute time steps over 96 hours. A positive spike on the plot indicates that the pump is active and on in scenario 8 but is off in the baseline, and vice versa for a negative spike. The green and blue plots correspond to the water level in Tower Street tank over 96 hours for both scenarios. The horizontal red and orange lines indicate the trigger water levels in Tower Street that deactivate and activate the main pump, respectively. The data (not presented) showed that the spikes in the plot are not occurring at relevant times (i.e. the pump turns off for one 10 minute increment but is on for the previous time steps and turns back on for following time steps) and never occur at peak usage (peak time occurs when Tower Street water levels dip in the plot) or outside of the range of orange and red trigger lines. The nature of the EPANET2 model turns a pump off or on if during the timestep the water level triggers the upper or lower limit (Rossman 2000). Appendix B provides an excerpt of the EPANET2 User Manual extended period simulation rules. This relationship can be seen in Figure 3.4 where the black spikes correspond to when scenario 8 or the baseline scenario water levels in Tower Street trigger a limit and the other scenario does not. However, in reality the tank controls would be adjusted to maintain an efficient pumping schedule. EPANET2 does not reflect the adjustment of controls. The data was corrected to account for these adjustments. If a pump was on in one scenario and off in another, the spike in energy (from the brake horsepower equation) was rejected from the summations. The same methodology was applied to all active pumps. Equations (7) and (8) were then used to calculate the total pumping energy requirements across all network pumps.
Figure 3.4: The difference in flow values at WTP pump 1 between Scenario 8 and the baseline, and water levels in Tower Street tank for the baseline scenario and Scenario 8 with upper and lower water level limits corresponding to the pump’s off/on controls

Step 5: Calculate the system indicators to compare the areas on the basis of energy and water savings.

The water use was calculated based on average daily nodal flow for the entire network. The indicators were calculated using equations (7)-(10). Table 3.8 summarizes the water demand, energy use, percent savings, and energy indicators for the baseline and conservation scenarios. The water savings from the residential target areas in Table 3.8 appear insignificant as a percent savings, but individually account for an approximate average of 100,000 L/day. If all scenarios were implemented, the potential city-wide water savings would be 1,730,000 L/day for a total of
630 ML/year. The trends in Table 3.8 are discussed in the following paragraphs by referring to scatter plots and visual representations of the results.

3.6.1 Pumping Energy and Water Demand

Figure 3.5 depicts a scatter plot of the daily pumping energy requirements and the average daily water demand for the entire network where each point on the plot represents the model results for a specific conservation scenario. The Central and East conservation scenarios are plotted as separate series to distinguish that changes made in the East are likely to stimulate a response in the East-end network components that differs from the Central response. The Central and East are plotted separately in all graphs for this reason. Referring to the Central data points, pumping energy and water demand shows a strong positive linear relationship for the range studied. The data points from the East do not follow the same linear relationship defined by the Central data points and shows no discernible relationship when viewed independently. The following explores the influence of spatial distribution of network components and network characteristics (such as pipe age, pump schedules, etc.) on the energy savings.
Table 3.8: Percent changes in water use and energy use, energy elasticity, and energy intensity for baseline scenario and 16 water conservation scenarios.

<table>
<thead>
<tr>
<th>Area</th>
<th>Water Demand (ML/day)</th>
<th>Mechanical Energy (kWh/day)</th>
<th>Change in Water (% saved)</th>
<th>Change in Energy (% saved)</th>
<th>Energy Elasticity (%E/%Q)</th>
<th>Energy intensity (kWh/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>57.45</td>
<td>10356.5</td>
<td>-</td>
<td>-</td>
<td></td>
<td>0.1803</td>
</tr>
<tr>
<td>Area 1</td>
<td>57.39</td>
<td>10355.6</td>
<td>0.098</td>
<td>0.009</td>
<td>0.088</td>
<td>0.1805</td>
</tr>
<tr>
<td>Area 2</td>
<td>57.32</td>
<td>10354.3</td>
<td>0.218</td>
<td>0.020</td>
<td>0.094</td>
<td>0.1806</td>
</tr>
<tr>
<td>Area 3</td>
<td>57.40</td>
<td>10355.7</td>
<td>0.075</td>
<td>0.007</td>
<td>0.092</td>
<td>0.1804</td>
</tr>
<tr>
<td>Area 4</td>
<td>57.40</td>
<td>10355.7</td>
<td>0.075</td>
<td>0.007</td>
<td>0.100</td>
<td>0.1804</td>
</tr>
<tr>
<td>Area 5</td>
<td>57.32</td>
<td>10354.1</td>
<td>0.224</td>
<td>0.022</td>
<td>0.100</td>
<td>0.1807</td>
</tr>
<tr>
<td>Area 6</td>
<td>57.40</td>
<td>10355.6</td>
<td>0.086</td>
<td>0.008</td>
<td>0.092</td>
<td>0.1804</td>
</tr>
<tr>
<td>Area 7</td>
<td>57.40</td>
<td>10355.7</td>
<td>0.086</td>
<td>0.007</td>
<td>0.087</td>
<td>0.1804</td>
</tr>
<tr>
<td>Area 8</td>
<td>57.28</td>
<td>10354.2</td>
<td>0.282</td>
<td>0.022</td>
<td>0.078</td>
<td>0.1808</td>
</tr>
<tr>
<td>Area 9</td>
<td>57.22</td>
<td>10353.5</td>
<td>0.390</td>
<td>0.028</td>
<td>0.073</td>
<td>0.1809</td>
</tr>
<tr>
<td>Area 10</td>
<td>57.36</td>
<td>10355.2</td>
<td>0.147</td>
<td>0.012</td>
<td>0.079</td>
<td>0.1805</td>
</tr>
<tr>
<td>Area 11</td>
<td>57.32</td>
<td>10354.6</td>
<td>0.216</td>
<td>0.018</td>
<td>0.083</td>
<td>0.1806</td>
</tr>
<tr>
<td>Area 12</td>
<td>57.21</td>
<td>10352.9</td>
<td>0.414</td>
<td>0.034</td>
<td>0.082</td>
<td>0.1810</td>
</tr>
<tr>
<td>Area 13</td>
<td>57.32</td>
<td>10354.5</td>
<td>0.216</td>
<td>0.019</td>
<td>0.087</td>
<td>0.1806</td>
</tr>
<tr>
<td>Area 14</td>
<td>57.44</td>
<td>10357.3</td>
<td>0.017</td>
<td>-0.008</td>
<td>-0.478</td>
<td>0.1803</td>
</tr>
<tr>
<td>Area 15</td>
<td>57.26</td>
<td>10359.6</td>
<td>0.317</td>
<td>-0.030</td>
<td>-0.095</td>
<td>0.1809</td>
</tr>
<tr>
<td>Area 16</td>
<td>57.36</td>
<td>10353.3</td>
<td>0.155</td>
<td>0.030</td>
<td>0.197</td>
<td>0.1805</td>
</tr>
</tbody>
</table>
3.6.2 Energy Intensity and Energy Elasticity

The scatter plot in Figure 3.6 shows the calculated energy elasticity indicator for each scenario plotted against total water demand. It is apparent from the values in Table 3.8 and the near-horizontal line in Figure 3.6 that the energy response to changes in water use is relatively inelastic, indicating that the modest water savings do not produce significant energy savings in this network.
Figure 3.6: Relationship between energy elasticity and average daily demand

Figure 3.7 presents the relationship between energy intensity and daily water demand. Having established that the energy use shows only a slight positive elasticity in response to water savings, the energy intensity of the network would increase with water savings because the system is consuming relatively more energy per cubic metre of water. In other words, the rate of savings of water is higher than that of energy (0 < e < 1), so the ratio of energy to water increases as water demand decreases. This is apparent from the negative linear relationship in Figure 3.7.
The geographic distribution of the energy intensity and energy elasticity are visually represented in Figures 3.8 and 3.9, respectively. Referring to the definition of energy intensity, water savings applied to the particular area cause a response in the overall pumping energy requirements of the network. Therefore, Figure 3.8 indicates that increasing the geographic distance from the WTP does not relate to reduced energy intensity in Kingston Central and Kingston East. If we consider the expected response from a simple one-pipe network, it would have followed that the further a node is from the source, the more significant the pumping energy savings would be when the nodal demand decreases because if water use was reduced in that particular area, there would be less water travelling to a relatively further distance. As apparent in Figure 3.8, this was not the case for the Kingston Central and Kingston East.
Figure 3.8: Energy intensity map for water conservation target areas

- Water Pump
- Water Tank

**Energy Intensity (kWh/m³)**

- N/A
- 0.00001 - 0.18029
- 0.18030 - 0.18033
- 0.18034 - 0.18043
- 0.18044 - 0.18051
- 0.18052 - 0.18053
- 0.18054 - 0.18065
- 0.18066 - 0.18076
- 0.18077 - 0.18091
- 0.18092 - 0.18097
The energy elasticity throughout the city is shown in Figure 3.9. Central Kingston shows a gradual increase in energy elasticities from south-east to north in the pressure zone. The result indicates that the energy requirements for pumping water to the downtown core of the network are more responsive to water savings than the surrounding neighbourhoods. In other words, water savings close to WTP produce a higher percent savings in energy use than water savings applied further from the WTP.

It was established in Figure 3.8 that energy intensity does not have a predictable spatial relationship to the WTP in response to water savings, and now from Figure 3.9 that the elasticity decreases as the distance required to pump water from the WTP increases. The north-west areas of Kingston Central with lower elasticities (Figure 3.9) generally appear with higher intensities (Figure 3.8). The relationship between the indicators is shown in the scatter plot in Figure 3.10. The energy intensity indicates that the pumps are using more energy per cubic metre of water in the same areas that elasticity is low. This occurs because the percentage change in water demand is higher than the percentage change in energy use, causing a high energy intensity value and a low elasticity value.
Figure 3.9: Energy elasticity map for water conservation target areas
3.6.3 Proximity to Network Components

Kingston Central

One reason why energy intensity and elasticity may have been unresponsive to the relative distance from the WTP is because the pumping schedule for the WTP is controlled by water levels in the Tower Street tank. Tower Street tank and the pumps at the WTP are the only active network components in Kingston Central. The Third Avenue pumps and reservoir are not active in the current version of the network model and therefore have no impact on the outcome of the study. To explore the relationship, the average storage head over 96 hours in Tower Street tank is
plotted in Figures 3.11 and 3.12 and visually overlaid on the energy intensity and elasticity maps in Figures 3.13 and 3.14.

The scatter plot in Figure 3.11 show that the water level in Tower Street tank responds to the nodal water demand. The hydraulic explanation for the relationship in Figure 3.11 is that the greater the reduction in water demand, the lower the pipe flows in the network, which in turn leads to reduced frictional headloss. The reduced demand at the end-nodes therefore causes higher hydraulic grade lines (HGLs) at the nodes near the tank, and thus a higher water level in the Tower Street tank. Higher water levels in the Tower Street tank due to higher water use reduction correspond to lower pumping energy use (Figure 3.12). A higher Tower Street tank water level (a higher HGL) also corresponds to a higher HGL at the WTP. The higher HGL at the WTP causes the pumps to operate at a higher HGL on their pump curves and to reduce the flow and overall pumping energy in the network.

Having established that the Tower Street tank influences the system, the discussion of spatial distribution should focus on the location of tank. However, the maps in Figures 3.13 and 3.14 do not show a distinct pattern in relation to the tank, indicating that the energy intensity and energy elasticity are not related to the distance of each target area from the tank. However, it is clear from the plots in Figures 3.11 and 3.12 that a relationship between the tank’s response to change in water demand and the energy indicators exists. This relationship is explained by the relative water savings and energy elasticity for each area. Since the elasticity values are low, areas with the highest water savings have the highest energy intensities. These areas have the highest energy intensities because water use is decreased more than energy use (on a percent basis) and thus the pumps spend more energy pumping a cubic metre through the system. Areas corresponding to lower water reductions have higher elasticities (more energy saved on percent
basis than water) and will correspond to lower HGL at nodes near Tower Street tank and therefore a lower water level in Tower Street tank. These areas also have the lowest energy intensities (because of less water savings).

Figure 3.11: Relationship between time-averaged Tower Street head and average daily demand
Figure 3.12: Relationship between pumping energy and time-average Tower Street head
Figure 3.13: Energy intensity and time-averaged Tower Street head for target areas
Figure 3.14: Elasticity and time-averaged Tower Street head for target areas
Kingston East

In the East, CFB tank water levels are responsible for controlling the James Street booster station pumping schedules. The same relationships that were established in Kingston Central with regard to tanks affecting the pumping energy requirements hold true in the East. The negative elasticity values in the East are in response to the water level in the tanks and standpipes. Figures 3.15 and 3.16 plot the energy use and water demand against the East-end storage components (the baseline scenario indicated by a black data point). The two scenarios with water use lower than the baseline that do not produce energy savings do not show increased storage head in CFB, which controls the booster station at James Street. The scenario that produces energy savings (positive energy elasticity) is located in the south and to the east of the CFB tank. The scenario reflects the savings in the higher water level in the Milton Street standpipe. Since CFB controls the standpipe levels as well, it is likely that the positive elasticity is occurring because the savings are registered in the water level controls at CFB. The effect of water savings on energy use is likely dampened by the presence of three storage components that regulate water pressures in the East.
Figure 3.15: Relationship between average daily demand and East-end storage
Figure 3.16: Relationship between pumping energy and East-end storage

### 3.6.4 Network Age

Figure 3.17 shows an overlay of pipe age on the energy intensities throughout the network. Visually, network age and energy intensity offer no visual relationship between older pipe configurations and higher energy intensities. It might be expected that when older pipes are both contained in and feed water to a given area, that the energy intensity of the network in response to water conservation in that particular area would decrease (implying that saving water in an energy intensive area would decrease overall energy needs). The lack of relationship may indicate that proximity of a conservation area to major network components (reservoirs, tanks, and pumps) has a larger influence on energy intensity, rendering the impact of network age (and by extension pipe roughness) undetectable.
Figure 3.17: Energy Intensity and pipe ages for target areas
A visual inspection of the overlay of pipe age on the energy elasticity map in Figure 3.18 shows a potential relationship between pipe age and energy elasticity. The older pipes in the downtown core correspond with the higher energy elasticity values. The system produces higher energy savings per cubic metre in the areas with higher pipe friction values and higher incidences of leaks, and vice versa. Interestingly, energy intensity does not respond in the same way as energy elasticity to pipe age. A likely explanation for the energy intensity values is that water savings were lowest in the areas in the downtown core and therefore the water percent savings were smaller in relation to the corresponding energy percent savings.

3.6.5 Energy Savings from Water Conservation

The case study considered only modest adoption rates on small geographic areas. The localised water savings from each neighbourhood rarely produce significant energy savings for the overall network. It is apparent that small savings are not going to yield any substantial changes for the utility, but the cumulative effect of the savings can offer the utility small savings on bottom line expenses and provide incentive to set higher conservation targets. From the perspective of the utility, an important take away is that water conservation can be achieved without producing significant changes to the pumping energy requirements.

The initial finding showed that the WTP pumps were largely unresponsive to various levels of water conservation. It is likely that for the small levels of water conservation considered, the Tower Street tank system controls, which maintain pressure stability in the network, and the complex network design dampen the energy response to water use fluctuations. Real networks are built with redundant loops in case of emergencies or changes in service, to maintain adequate pressure levels throughout the network, and to minimize water age in pipes to ensure the highest
Figure 3.18: Elasticity and pipe ages for target areas
level of safety for end-users. The relationship for real networks is significantly more complicated than assuming that water pumped a greater distance results in higher energy use. Optimizing pump schedules and the location of future tanks in partnership with water conservation may be a strategy that could offer more significant energy savings for the utility.

3.6.6 Limitations

The case study assumed that the water conservation measures are implemented and adopted instantaneously at the start of the simulation. In reality, the adoption of water-efficient devices would be gradual and the adoption rate of the different devices chosen by each household would vary. In order to implement this delay, a time dependent model would need to be used.

Network components such as pump operations and tower water levels influenced the outputs of the model. In practice, a utility would adjust its pump operations and tower controls to maintain appropriate water levels and to maintain optimal pump efficiency. These adjustments are not accounted for in the simulations.

3.6.7 Future Work

The goal of the water conservation planning tool is to provide a realistic initial assessment of which neighbourhoods can offer the most water savings given the various socio-economic demographics within a municipality and which areas of a network offer the greatest potential energy savings given the characteristics of the specific distribution system. The next step for the utility would be a cost-benefit analysis of the water conservation scenarios. From the initial assessment, it would be useful to do a more detailed time dependent computational model that ran a large number of simulations including time delayed conservation plans, pump schedule adjustments, and inclusion of stochastic design parameters.
3.7 Conclusions

This thesis presents a new planning methodology for water utilities looking to reduce their water use and energy requirements through targeted water conservation measures. The objective was to design a tool that provides information to help prioritize water conservation plans based on socio-economic factors and to highlight the importance of accounting for spatial parameters when calculating potential energy savings. The Utilities Kingston case study indicated that energy savings due to localized water conservation are influenced by the proximity of major network components such as tanks and pumps. The study did not find a visual relationship between pipe age and energy intensity for the specific network but did indicate that energy elasticity and pipe age are related. The study used two main indicators to represent the variance in water and energy savings, an energy intensity indicator and the elasticity of water to energy. Although the study considered only a snapshot in time of the utility’s operation, the methodology has merit as a planning tool for implementing water conservation plans with specific demographics in mind. The utility can use information about household type and location to provide incentives for end-users, with the knowledge of which network areas offer the highest energy savings per cubic meter of water saved. With this initial study, the municipality can conduct more detailed modelling of their network to understand how to adjust their network operations to be most efficient in response to reduced water demand.
3.8 References


CHAPTER 4
Summary and Conclusions

Municipal water utilities operate on tight financial budgets to deliver safe and reliable service to consumers. Operators are constantly dealing with ongoing maintenance, leaks and unexpected breaks, and upgrades to meet growth and expansion. A significant portion of operational costs for utilities are spent on moving water and wastewater through the distribution network. In light of these realities, many practitioners are looking at how they can structure their operations and management to lower costs by reducing energy and water consumption.

The work in this thesis presented a demand-side management water conservation strategy. The thesis contributed to the field of water conservation by:

1. Creating a water conservation planning framework based on reducing both water consumption and energy use.
2. Including socio-economic factors to produce localized residential water conservation plans.
3. Conducting an analysis of potential water savings for each residential sub-group based on a fixture-by-fixture household water conservation model.
4. Developing energy indicators that assess the energy response to water savings for localised geographic areas in a distribution network.
5. Applying the new methodology to a real all-pipe network case study.
Chapter 3 presented a new methodology and case study results for a water conservation planning tool. The methodology was applied to the City of Kingston Central and East distribution network to illustrate the relationship between geographic location and energy savings due to water conservation measures applied throughout the city. A fixture-by-fixture water conservation model was presented to quantify household water use and potential water savings. An energy balance for a control volume of a water distribution network was developed and later used to calculate the total mechanical energy used to distribute water throughout the system. Two indicators were developed: the energy intensity indicator, which represented the mechanical energy in kilowatt-hours required to move one cubic metre of water through the distribution system for a given scenario, and; the energy elasticity indicator, which related each scenario to the baseline data and represented the percent change in energy for a one percent change in water demand. A case study for the Kingston, Ontario water distribution network was presented. For marginal water savings, the energy response was found to be inelastic to changes in water demand. The low energy elasticity explained why the energy intensity of the network increased in response to reduced water demand. The case study concluded that:

1. The water levels in the tanks had the most significant influence on the energy savings in the network because the network pumps are controlled by the water levels in the tanks.
2. An area’s distance from the water treatment plant did not relate to the either of the energy indicators.
3. The low elasticity values were due to insignificant energy savings.
4. Energy intensities were lowest in areas with low water savings because energy was inelastic.
Appendix A
Figure A.3: City of Kingston all-pipe network model (pipe diameters)
Figure A.4: City of Kingston all-pipe network model (pipe materials)
Figure A.5: City of Kingston all-pipe network model (node elevations)
Appendix B

As added reference, the follow excerpt from the EPANET2 User Manual explains how the extended period simulations calculate each time step:

“a. After a solution is found for the current time period, the time step for the next solution is the minimum of:

- the time until a new demand period begins,
- the shortest time for a tank to fill or drain,
- the shortest time until a tank level reaches a point that triggers a change in status for some link (e.g., opens or closes a pump) as stipulated in a simple control,
- the next time until a simple timer control on a link kicks in,
- the next time at which a rule-based control causes a status change somewhere in the network.

In computing the times based on tank levels, the latter are assumed to change in a linear fashion based on the current flow solution. The activation time of rule-based controls is computed as follows:

- Starting at the current time, rules are evaluated at a rule time step. Its default value is 1/10 of the normal hydraulic time step (e.g., if hydraulics are updated every hour, then rules are evaluated every 6 minutes).
- Over this rule time step, clock time is updated, as are the water levels in storage tanks (based on the last set of pipe flows computed).
- If a rule's conditions are satisfied, then its actions are added to a list. If an action conflicts with one for the same link already on the list then the action from the rule with the higher priority stays on the list and the other is removed. If the priorities are the same then the original action stays on the list.
- After all rules are evaluated, if the list is not empty then the new actions are taken. If this causes the status of one or more links to change then a new hydraulic solution is computed and the process begins anew.
- If no status changes were called for, the action list is cleared and the next rule time step is taken unless the normal hydraulic time step has elapsed.

b. Time is advanced by the computed time step, new demands are found, tank levels are adjusted based on the current flow solution, and link control rules are checked to determine which links change status.” (Rossman 2000)


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