Abstract

The research presented in this thesis focuses on developing a water-use forecasting method using an agent-based model. The novelty of this method is that it allows for a given population to be represented heterogeneously and that the household are connected amongst themselves and can transmit information and modify their behaviours. The model is showcased using a case study in Kingston, Ontario where households are modeled at the individual level as agents that separate water use into 6 household fixtures. Agents are given a set of attributes that enable them to make decisions and adapt behaviour based on social-networks and communication. Available data from Statistics Canada is used to characterize 40 neighbourhoods within Kingston, Ontario. The modelling framework is utilized to test population responses and potential water savings achieved through conservation campaigns. The research consists of evaluating the change in water demand using the model and running the results into a pipe-network hydraulic solver (EPANET 2.0) to calculate the change in energy use from the distribution system associated with conservation programs. The model and the case study are used to answer a series of research questions concerning the sensitivity of the ABM to social communication parameters, the potential water and energy savings that are achievable in the Kingston distribution system and finally, how the spatial distribution of water savings affects energy savings in the Kingston system.
Co-Authorship

Alexandre Tourigny is the primary author of this thesis. Dr. Yves Filion, provided editorial comments in addition to intellectual supervision for all chapters of this work. Chapters 2, 3 and 4 were written as part of independent manuscripts in which Dr. Filion is co-author.
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Chapter 1

Introduction

Water is ubiquitous in our lives, we use it every day as it is essential to our most basic needs. The importance of sustainably managing this vital resource cannot be over-stated. There are however, many challenges associated with sustainably managing our supply of freshwater. In many North American cities, peoples’ needs for water are generally met by means of the urban water cycle. The urban water cycle generally consists of taking raw water from its source, treating it, and distributing it via a network of pressurized pipes where it reaches the end user. The wastewater is then collected, transported by a series of sewers, treated and released into the natural environment. Sustainably managing resources requires the need for both social and technical solutions. End users affect water infrastructure as they design, build operate and ultimately use these systems while the system themselves affect end-users as they provide them with clean reliable drinking water and sanitation. The work presented in this thesis focuses on modelling one instance of this socio-technical dependence, specifically, the relationship between water-users, distribution networks and energy use.

1.1 Energy Requirements for Water Distribution Systems

Water is transported through a distribution network of pipes sometimes over great distances from the treatment plant to the end user. Large energy expenditures are often required to convey the resource over these distances. Mechanical energy is added to the distribution system through the use of pumps. Energy is also supplied to the system to overcome frictional energy losses, satisfy genuine user demand and leaks, and overcome sometimes sizable differences in ground elevation in topographically challenging distribution systems. Supplying water is therefore energy intensive. In Ontario, municipalities consume more electricity than any of the industrial sectors.
with the exception of pulp and (MOECC, 2008). In the Province of Ontario, the delivery of both water and wastewater services are the largest electricity consumers for most municipalities (Maas, 2009). With household water consumption contributing to a significant portion of total demand, a decrease in domestic water use could lead to important energy savings for water providers.

1.2 Water Conservation
As cities are expanding, municipalities are tasked with delivering an increasing amount of clean water while drawing from limited resources. Water is used for domestic consumption, industry, energy production, commercial purposes, and agriculture. Demand reduction techniques such as fixture replacement programs can be an attractive option for conservation planners as it allows water users to receive the same level of service without modifying their behaviour all the while achieving the desired water reductions. Water efficiency or conservation campaigns are often spearheaded by municipalities in an attempt to reduce residential water demand. Traditional demand reduction strategies can include legislative approaches such as outdoor watering restrictions, economic approaches such as raising water rates and fixture rebate programs which offer home owners a financial incentive to retrofit their homes with more water efficient fixtures. The City of Kingston is used as a case study for this work. The City is currently pursuing demand reduction strategies which are administered by Utilities Kingston. Currently, no reduction targets have been set and very little is done in terms of public information campaigns other than the cities website. This research examines the potential water and associated energy reductions that could be achieved through retrofitting Kingston households with water efficient fixtures.

1.3 Simulating Socio-Technical Systems
Modelling systems can be a useful exercise as it provides the ability to test multiple hypotheses or cases using simulations (Winz et al., 2009). Hydraulic models provide the opportunity to simulate a range of scenarios and hydraulic conditions, useful information can then be extracted to
evaluate infrastructure performance under these hydraulic conditions. They are extremely useful tools however, they do not account for motivations that may cause these change in hydraulic conditions when they are user driven. Undertaking socio-technical models that couple social behaviour and technical systems can help develop a better understanding of the consequences that human behaviour can have on infrastructure design and operations. A simulation approach provides the opportunity to test multiple scenarios. Social and technical models can be coupled together to study how human behaviour can affect technical systems. Water-use is an ideal candidate for this type of coupling considering the social dimensions of water use and the multiple infrastructure systems required to manage water resources. Relatively simple models can be built if limited information is available while a more complex approach can be undertaken if access to data is more readily available. Agent-based models (ABMs) are particularly well suited for modelling social behaviour based on how they are structured (van Dam et al. 2013). The architecture of an ABM consists of a network of autonomous agents that can be connected with each other within an environment. The agents can transmit information to each other and change behaviour upon receiving information. Simple rules and interactions between agents can lead to complex and emergent behaviour. This thesis develops an ABM to model the interactions between water users and water distribution networks.

Decision support systems can help water managers tackle challenges inherent in water resources management. Decision support tools can be used to systematically evaluate infrastructure performance under a range of potential scenarios and contribute to better decision making. The research presented in this thesis develops and demonstrates a simulation approach that is used as a decision support tool for water managers. The approach couples a social and a hydraulic model to capture the relationship between end-users and infrastructure performance, particularly distribution networks. The social model simulates residential water users that modify their water
use through the adoption of low-flow fixtures. The water users are motivated to adopt these fixtures through social interactions with their neighbours and by receiving information from their local water utility. The new hydraulic conditions brought on by reduced water user is then evaluated through a hydraulic network solver to analyze the energy requirements for the reduced demand.

1.4 Thesis Objectives

Four specific research questions and three objectives were developed for this thesis. They are as follows:

The research questions that underpin this thesis research are the following:

1. How do social network parameters that govern connections between inter-agent communication and innovation diffusion within an ABM affect the rate and speed of adoption of low-flow technologies within that model?
2. What is the potential of low-flow technologies (e.g., water-efficient toilets, showers, washing machines and dish washers) at reducing water use in the City of Kingston?
3. To what extent can a reduction in water use produce a corresponding reduction in energy use for pumping and treatment of clean water within the Kingston distribution system?
4. To what extent do geographically-targeted conservation measures can reduce water and energy use in the Kingston distribution system.

1.5 Thesis Organization

The thesis is organized in a series of chapters. Chapter 1 introduces the topic, provides background on the themes of this work and outlines the main research questions and objectives. Chapter 2 presents a literature review of the relevant work undertaken in similar areas of research. Chapter 3 is a technical chapter where an ABM and the results of a series of sensitivity analyses on the ABM parameters is presented. Chapter 3 examines research questions 1, 2, 3. In chapter 4,
the ABM is developed further, and the fourth research question is considered. A conclusion and summary of the results is presented in chapter 5.

1.6 Publications
Sections of this thesis have been published as part of conference proceedings or are currently under review for journal publication:


1.7 References


http://news.ontario.ca/archive/en/2008/05/26/Municipalities-can-get-a-big-boost-toward-energy-savings.html


Chapter 2

Literature Review and Background

2.1 Introduction
Chapter 2 presents a review of the relevant literature of the major themes of this research. The major themes are water conservation modelling, the link between energy and water distribution, water conservation research and agent-based modelling for water resources planning and managements. All of these themes were central to the development of technical chapters 3 and 4.

2.2 Water Conservation
Water efficiency or conservation campaigns are often spearheaded by municipalities in an attempt to reduce residential water demand. Traditional demand reduction strategies include legislative approaches such as implementing outdoor watering restrictions, economic approaches such as increasing rates, and fixture rebate programs which offer a financial incentive to retrofit buildings with more water efficient fixtures. Community-based social marketing (CBSM) is a marketing technique often used as a tool to remove barriers to change or to entice people to adopt a certain product. The strategy is often adopted for environmental campaigns rather than traditional products. The approach can be used to solicit a change in behaviour such as undertaking some conservation action rather than traditional marketing techniques that are aimed at increasing consumption. CBSM relies on initiatives that are mostly conducted at the community level that rely heavily on communicating directly with users and emphasizing social norms around a product or behaviour (Kennedy, 2010). A key element of this strategy is using word-of-mouth to inform individuals about a product or campaign. Word-of-mouth describes the mechanism through which information can be disseminated throughout a population. It is a way to diffuse information through direct contact between people and generally comprises of individuals informing their neighbours, peers, friends about a product or opinion who may then modify their
opinion or adopt a product after the interaction (Chen et al., 2013). This approach often complements other strategies such as information campaigns and incentives (Dietz et al, 2009).

Several types of education campaigns are used by municipalities as a strategy for demand management. These types of strategies rely on information being communicated to the intended audience (water users) and that users modify their behaviour in response to the message. The target audience must be convinced of the merits of water reductions and the success of these campaigns rely on widespread adoption of water reduction measures. Attari (2014) makes an important distinction between “curtailment actions” which constitutes behavioural modifications that individuals can take to reduce water and “efficiency actions” to describe technological improvements such as adopting more efficient fixtures to reduce water use. Inskeep & Attari (2014) have found that individuals tend to underestimate the amount of water they use and have a poor perception of the most effective water reduction measures which can act as a barrier to the widespread adoption of more efficient appliances. Community-based-social marketing (CBSM) techniques have been applied to water conservation campaigns to try and overcome these barriers which make heavy use of social norms to achieve their objectives (Kennedy, 2010). Social marketing is a tool that can be used to promote behavioural change (Lowe et al., 2014) and can be utilized in the context of a water conservation campaign. The social marketing approach is focused on educating the public to instill a social norm as a mean to promote a certain type of behaviour (McKenzie-Mohr, 2001). Successful CBSM campaigns are most effective when they combine policy tools such as incentives and appeals to the public along with social marketing which makes use of social networks and social norms (Dietz et al 2009). Social norms have been found to influence consumer behaviours as it relates to water use, for example Ferraro and Price (2013) found that messages that were sent to consumers where social comparisons were included such as comparing the household’s water use to the county’s median household water use were
more effective at reducing water use than strictly providing technical information while Brent et al. (2015) found that campaigns that made use of social norms increased participation rates in rebate programs. In another example documented by Walton & Hume (2011), residents were asked to limit their personal water use to 140 l/person/day. Community leaders and local celebrities all contributed to the effort in spreading the message to influence the public to participate. In the end, the campaign was a success and the target was achieved. These campaigns rely on word-of-mouth to guide users to communicate and influence their friends and neighbours to conserve water. Another study found that people who received water-saving devices combined with personalized communication (people would receive water-saving fixtures and have help installing them) where more likely to install the devices (Campbell and Larson 2004).

Generally, information campaigns are used to inform the public on why conservation is important and on how individuals can achieve water savings. Water conservation campaigns that rely on educational programs have proven to be an effective tool to promote water saving measures. Research undertaken to measure the effectiveness of these campaigns have reported between 2 to 8% annual water savings (Inman & Jeffrey, 2006) linked to education campaigns. In Canada, most conservation campaigns include some form of public outreach and education (Waller & Scott, Canadian Municipal Water Conservation Initiatives, 1998). Educational campaigns communicate with their audiences using a variety of mediums including: radio and television advertisement, outreach in schools, pamphlets, customer feedback programs and through social media. Estimating customer responses to campaigns aimed at reducing water use can be a challenge. Silva et al. (2010) surveyed a number of homes across six American cities; the survey asked residents a variety of questions pertaining to individual attitudes towards conservation including their preferred means of receiving information about water conservation and the effectiveness of water utility messages among other related topics. Results from the Silva et al.
(2010) survey indicated that 62% of respondents would participate in a rebate program if given the option, 18% of respondents indicated having engaged in conservation behaviour after receiving promotional material through a mail-in program and 2% did so as a result of peer pressure. The reality is that, individuals are bombarded with information every day and will not necessarily pay attention to the water conservation messages. For instance, Howarth & Butler (2004) found that when residents received a leaflet at their homes which promoted water conservation behaviour, only 17% of respondents remembered the campaign one month after receiving the leaflet.

2.3 Water Conservation Modelling

Water reduction strategies are important considering the increasing water scarcity in some areas in the world and the energy associated with treating, pumping and heating the public water supply (Rothausen & Conway, 2011). Municipalities are often tasked with developing water conservation strategies aimed at reducing domestic water use. Water-efficient fixtures are designed to reduce the volumetric flow rate of an appliance without changing the level of service experienced by the end-user. Previously measured flow rates in homes before and after a fixture retrofit have shown a decrease in water use associated with low-flow fixtures (DeOreo et al. 2001; Mayer et al. 2004; DeOreo et al. 2012; Lee et al. 2013).

Previous research has also focused on developing models that estimate the potential for water reduction. Whitcomb (1990) used a multivariate approach with a control group to simulate a 6.4 percent per capita decline in water use from the installation of low-flow showerheads and a 2.1 percent decline from the installation of low-flow toilets. The Whitcomb (1990) model included the exploratory variables of household composition (age of members), income, type of water bill and retrofitted appliances. Suero et al. (2012) developed analytical, regression and hybrid models to simulate water savings associated with the adoption of water-efficient appliances (retrofitted
toilets, clothes washers, faucets and showers). The results showed that water savings were achieved in over 90 percent of the homes retrofitted and the researchers concluded that although both technological and behavioural factors influenced total water savings in household, technological changes were more significant (Suero et al. 2012). Stochastic models have also been developed to estimate the effectiveness of conservation measures while taking into account uncertainty (Rosenberg 2007).

2.3 The Link Between Energy and Water Distribution

Given the large amounts of energy required to transport water, previous research has focused on the link between energy use and water distribution systems. Sanders & Webber (2012) created a national benchmark for all water related energy use in the United States & Liner (1998) developed WATERGY to simulate energy savings associated with water reductions from residential, commercial and non-revenue water. Pelli & Hitz (2000) developed two metrics in order to evaluate water distribution network performance in terms of energy use. The first metric was a structural indicator that described how the system layout and the spatial distribution of water users effected energy use while the second metric, termed a quality indicator, examined the ratio between effective and minimum energy. Cabrera et al. (2010) developed a set of water distribution system energy metrics to help water managers characterize system wide energy performance. The metrics were derived to quantify energy losses due to leaks, friction of pipe walls and overpressure. The authors further developed their approach in Cabrera et al. (2015) by formulating additional metrics to assess the energy efficiency of a pressurized system. Spang & Loge (2015) developed a method to characterize the spatial distribution of energy use in a water distribution system. The research showed that the energy efficiency of water distribution systems can vary throughout seasons and spatial location. The authors concluded that targeting specific geographic locations within a distribution system could lead to greater energy savings. Santosh & Barkdoll (2010) conducted a sensitivity analysis on seven municipal water distribution systems to
evaluate energy savings associated with a reduction in water demand, alteration of storage and pumping characteristics. The researchers found that a 20 percent reduction in demand could result in 13 percent energy savings and that 50 percent reduction in water demand would yield approximately 47 percent average energy savings. The household and system-level energy reductions achievable through harvesting rainwater and retrofitting households with low-flow fixtures was tested for the city of Toronto by Racoviceanu & Karney (2010). The authors found that a 54% water reduction could be achieved through the implementation of these strategies and that significant energy savings could be achieved from reduced heating, pumping and treatment of water. However the baseline scenario assumed no such fixtures were present in homes which could lead to an overestimation of water and energy savings.

Previous work has established a relationship between the adoption of low-flow fixtures and water use for individual homes (Mayer, et al., 1999; DeOreo, et al., 2001; DeOreo et al., 2016). At the household level, reductions in hot water use can lead to energy savings from water heating. Beal et al. (2012) used empirical household data from homes in Queensland Australia to estimate energy and greenhouse gas (GHG) savings that can be achieved through the adoption of water-saving fixtures. The study focused on energy savings related to hot water use. Chini et al. (2016) assessed the water and energy savings that could be achieved by upgrading a host of household appliances with more efficient WaterSense and Energy Star models. They developed cost abatement curves at both the national (U.S) and city level to determine the economic efficiency of adopting various appliances. A Material Flow Analyses model was used by Kenway et al. (2016) to conduct a sensitivity analyses on key parameters that effect water-related energy use in households. Data from seven households was used to calibrate their model and an additional 94 households for shower data. The authors found that changing key parameters such as shower
duration and flow rate can lead to significant household energy savings. Similar findings were also reported by (Binks et al., 2017).

2.3 Agent-Based Modelling for Water Resources Planning and Management

The objective of undertaking socio-technical models is to gain a better understanding of the consequences that human behaviour can have on infrastructure design and operations. Agent-based models (ABMs) have been used as a tool to model the human interactions with infrastructure design in response to policy changes (Berglund, 2015). Current research in water resources management using ABMs tends to couple agent-based models to hydrologic models in order to better understand the interactions between infrastructure and end users. The effect of policy decisions has also been simulated using this technique. Models have been developed that simulate micro-level decisions by individual users that lead to emerging system properties. ABMs have been developed with varying complexity attempting to take into account factors at an individual level that affect water use behaviour. The objective is to account for the complexity that arises from multiple stakeholders involved in water management and recognize that planning can be viewed within a wider context of a complex adaptive system. In complex systems, system properties emerge that result from the cumulative interactions that take place between every component of a system. Understanding a single component in isolation is not enough to understand the entire structure (Siegfried, 2014). The agent-based framework is also well suited to model these complex systems (van Dam et al., 2013) in which cumulative interactions can create feedback loops and emergent behaviour. The effect of policy decisions for example, water restrictions due to droughts or conservation campaigns can be modeled by representing the various stakeholders as agents. Changes of policy such as water restrictions due to droughts or conservation campaigns are programs that seek to modify behaviour for end users. Agent-based modelling can account for these changes by incorporating agents who adapt their behaviour to external triggers within a modeled system.
Agents are used as tools for modelling complexity and are the fundamental building blocks in the agent-based modelling methodology (ABM). For ABM’s methodology, software entities known as agents exist as part of a larger system. The architecture of an ABM consists of a network of autonomous agents that can be connected with each other within an environment. The agents can transmit information to each other and change behaviour upon receiving information. Simple rules and interactions between agents can lead to complex and emergent behaviour. These entities can represent live or inanimate objects. The agents are autonomous and are assigned a set of attributes and behaviours that describe their individual state. They are situated within an environment in which they can perceive and from which they receive signals from known as events. The events can trigger the agents to update their behaviour (Berglund, 2015). Two fundamental types of agents exist: active or reactive. Reactive agents do not update their behaviour, they only respond to their environment and events, while active agents do update their behaviours (Berglund, 2015). Active agents can also be goal-seekers which solve problems in order to attain their objectives (Jennings, 1999). Agents can represent humans and the decision-making processes can be simulated using a variety of functions: econometric, social, cognitive, experience based, or threshold rules (An, 2012) depending on the question of interest. Athanasiadis et al. (2005) created DAWN, an ABM that coupled an econometric and social model in order to evaluate the potential effect of pricing policies on water use. The model was used in the region of Thessaloniki, Greece to simulate water use with response to policy changes. Lopez-Paredes et al. (2005) developed the FIRMABAR simulator in which agents updated their water consumption behaviour based on price, income, housing type and social attitude. The ABM featured a coupled territorial and social model that was used to simulate and test a range of water resource policies in Barcelona. Regulators, water appliance market and households were all represented as agents for the Residential Water Use Model (RWUM) created by Chu et al.
(2009). The regulators set the price, and the water appliance market agents monitored consumption and provided water efficient devices to the household agents. Kanta & Zechman (2014) coupled an agent-based consumer model with a watershed reservoir system model to evaluate inter-basin transfers in a case study. A pipe network model was coupled with an ABM to simulate the spread of a contaminant within a water distribution network as consumers and a utility manager agent react to the event by modifying consumption (Zechman, 2011). The Freshwater Integrated Resource Management with Agents (FIRMA) project used agent-based modelling to try and improve water resources planning and management through the use of ABMs. (Manchester Metropolitan University Centre for Policy Modelling, 2003) Several models have been developed under this initiative and have been applied to 5 areas throughout Europe. The ABM presented in this thesis models water users through the use of a stochastic water end-use model. The agents are connected amongst themselves and influence each-other to adopt water-efficient appliances.

2.4 Simulation Modelling Analysis and Statistical Techniques

The research presented in this thesis relied on the use of simulation. Scenarios were generated through computer software (Anylogic, 2016) and coded programs to study a system comprised of water users and evaluate how human interaction can play a role in modifying water use. Given the fact that human behaviour is inherently non-deterministic, stochastic models were created to capture some of the variability in human actions. The following section provides a brief description of the major statistical and modelling concepts that were used in the model design, and analysis of results.

2.4.1 Monte Carlo Methods

The concept of Monte Carlo Methods (MCM) is to develop a computer based analytical model that represents the behaviour of a system of interest (Ayyub & McCuen, 2011). The model is developed to predict the system’s behaviour under different set of operating conditions using a set
of both random and non-random variables as inputs. Because of the random parameters, many simulation cycles are executed, and a set of solutions is generated rather than one unique solution. These solutions are then analyzed using statistical techniques. The analytical and computational steps that are executed using a Monte Carlo simulation is summarized as follows (Ayyub & McCuen, 2011):

1. A computer model of the system is defined;
2. Random numbers are generated;
3. Random variables are generated;
4. The model is evaluated to generate results.
5. Results are interpreted using statistical techniques.
6. The efficiency of the system can be optimized, and the set of results can be studied to ensure convergence.

The system of interest for this thesis was a group of water users, specifically Kingston residents. The system was defined as a group of household water users that were connected amongst themselves and could exert influence between their neighbours. Random variables were used as model inputs to model water use, water users and their connections. Several simulations were executed for each experiment and the results were analyzed using statistical techniques described below. The outputs of interest were mean water use and the energy outputs of Kingston’s water distribution network. The following section provides a brief outline of the statistical concepts that were used in this work.

2.4.2 Random Number Generator

A random number generator is an algorithm that generates a random set of non-negative real numbers with an equal likelihood (Law & Kelton, 1991). The numbers that are generated can be normalized by dividing each value by the largest possible value, this results in a set of values that can be expressed as a random variable U which has a uniform distribution of continuous range
[0,1] (Law & Kelton, 1991). They are widely used in simulation as the numbers can be transformed to follow any distribution of interest. The Linear congruential method was used in the model presented in this thesis to generate random numbers.

2.4.3 Linear Congruential Method
The Linear Congruential Generator (LCG) is a pseudo-random number generator that generates a series of random numbers, that series is repeated and is dependent on the period. A seed value $X_0$ is chosen, is multiplied by a constant $a$ and incremented by a constant value $c$. The modulus $m$ is then taken and the result serves as the $X_i$ value for the next iteration which creates a recursive relationship.

$$X_{i+1} = (aX_i + c) \mod m$$  \[1\]

For $i=1,2,3…$

If the constants ($a,c$ and $m$) are given the same values throughout different simulation runs, the same sequence of random numbers will be generated. The numbers are not truly random as they are generated through a deterministic function however they do satisfy statistical tests of randomness. This can be helpful during experimental design and for troubleshooting. These random numbers are then transformed into random variates from a probability distribution function $X$. A variate is a random value $x_i$ chosen from a random variable $X$ as described above. The inverse transform method was used to generate random variates from the empirically derived discrete probability functions that were utilized throughout this research.

2.5 Inverse Transform Method
Random variates are generated from the discrete random variable $X$ from the cumulative density function $F(x_i)$ where:

$$F(x_i) = P(x \leq x_i)$$  \[2\]

The following steps were used to generate discrete random variables ($x_i’s$) as described in Ayyub & McCuen (2011).
1. A random number $u \in U[0,1]$ is first generated using the LCG described above.

2. $X_i$ is chosen such that $i$ is the smallest integer with $u \leq F_x(x_i)$

   Where $x_i$, $i = 1, 2, 3, \ldots, m$, are discrete values of the random variable $X$ with a cumulative mass distribution function $F_x(x_i)$.

### 2.5.1 Sampling Statistics

As the true mean and variance of the population is unknown statistical inference is used as an estimator. The sample mean provides a point estimate of the true mean and is calculated using the following relationship.

$$
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i
$$

Where $\bar{x}$ denotes the sample mean and $n$ the number of observations. Similarly, the sample variance $s$ is obtained using:

$$
s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2
$$

Confidence intervals are used to estimate the accuracy of the point estimate. The following relationship is used to obtain an interval estimate of the true mean $\mu$ with a $100(1-\alpha)$ % confidence interval.

$$
\bar{x} - t_{\alpha/2} \frac{s}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2} \frac{s}{\sqrt{n}}
$$

Where $t_{\alpha/2}$ is the $t$-value (taken from the student-T distribution) with $(n-1)$ degrees of freedom.

When random variables were included in the simulations (the case for the ABM but not the hydraulic model) sample means and sample variance of the results were used to create confidence intervals. These techniques rely on the results being normally distributed, this was confirmed to be the case through the use of a chi-squared goodness-of-fit test.
2.6 References


http://www.allianceforwaterefficiency.org/toilet_fixtures.aspx


http://www.allianceforwaterefficiency.org/Faucet_Fixtures_Introduction.aspx


Kingston: Utilities Kingston.


Chapter 3

Impact of Social Interactions between Water Customers on Water Use and Energy Use in a Canadian Water Distribution System

3.1 Abstract
This chapter presents the results of a sensitivity analysis performed to examine the impact of uncertain social parameters in an agent-based model (ABM) on the prediction of water use, energy use, and greenhouse gas emissions linked to pumping in a distribution system. The ABM was coupled with a water end-use model and the EPANET2.0 network solver to simulate the word-of-mouth communication and the adoption of water-efficient fixtures that lead to water use and energy savings in distribution systems. Three key ABM parameters (adoption probability, initial penetration rates and connections per agent) were found to have an important impact on the adoption rate of low-flow fixtures. Further, the increased adoption of four specific low-flow fixtures—toilets, showers, washing machines and dishwashers—were estimated to have the potential to reduce water use (9 percent) and energy use for pumping and treatment of (9 percent) within a mid-sized Canadian water distribution system. The water reductions observed indicates that, even though many homes are already equipped with water efficient devices, fixture replacement campaigns still have the potential to reduce water and energy use in distribution systems. The work provides an innovative framework that simulates human interactions and evaluates how these interactions can affect water, and subsequently, energy use in distribution systems. The results of the sensitivity analyses can be applied to inform the development of future ABMs that account for the social dimension of water use.

3.2 Introduction
Agent-based models provide the modeller with a tool to simulate social interactions between water users. Although this approach can be very useful, there is scarce data available and ABM
model parameters can be difficult to measure in practice. This introduces a high degree of uncertainty in the estimation of model parameters. The benefits of household water reductions are well known and are becoming important for some water-stressed regions in terms of both water and energy savings. Estimating the effectiveness of conservation campaigns can be a daunting task as there is uncertainty associated with social behaviour, the effectiveness of water-efficient appliances at reducing water use and the corresponding energy reductions in the water distribution system. These uncertainties motivate the following research questions presented in this chapter:

1. What is the impact of social ABM diffusion parameters on the rate and speed of adoptions of low-flow technologies?
2. What is the potential of low-flow technologies (e.g., water-efficient toilets, showers, washing machines and dishwashers) in reducing water use?
3. To what extent can a reduction in water use produce a corresponding reduction in energy use for pumping and treatment of clean water in a mid-sized water distribution system?

This chapter presents an agent-based model where agents are household water consumers that influence each other to adopt low-flow fixtures. The households are of varying types comprised of semi-detached, row houses as well as multi-residential units. The ABM is linked with a water distribution network model (EPANET2) to calculate the energy and greenhouse gas reductions achievable at the network level through water savings. The results from three separate, but related, sensitivity analyses are presented in order to establish: 1) the responsiveness of adoption rate to the social ABM parameters examined, 2) the level of water reduction achievable through the wide spread adoption of these fixtures, and 3) the level of pumping and treatment energy that can be saved from these water reductions. The City of Kingston is used as a test system for these three sensitivity analyses.
3.3 Kingston Distribution System

The City of Kingston is located in southeastern Ontario, Canada, on the eastern side of Lake Ontario and at the mouth of the St. Lawrence River. The water and wastewater works are owned by the City but privately operated by Utilities Kingston. The Kingston water distribution system includes 5 booster stations, 561 km of water mains, and 11 storage facilities (Utilities Kingston, 2015). The distribution system serves over 37,000 homes and businesses and pumps almost 25 million cubic meters of water every year to users (Utilities Kinston, 2015). In 2011, the pumping and treatment of drinking water represented 6 percent of the city’s GHG emissions (TriEdge & Associates, 2013).

3.3.1 Characterization of Neighbourhoods

The City of Kingston has been subdivided into 43 neighbourhoods that represent on average 5 to 7 street blocks with 400 to 700 residents per block. The Kingston distribution system and above-mentioned neighbourhoods are shown in Figure 3.3.1: City of Kingston water distribution system and neighbourhood delineations. Census data on housing statistics was used to characterize the neighbourhood profiles of the City of Kingston and to initialize the ABM model (City of Kingston, 2014). The census data included information on the number of occupied dwellings, the type of dwellings. Census data was enhanced with local data on the social and physical attributes of the Kingston neighbourhoods (Government of Canada, 2011).
3.4 Methods

The assessment of a target population’s potential to save water requires estimates on how quickly conservation measures will be adopted, the efficacy of these efficiency measures in reducing water use and the cumulative water savings of the reduction strategies. In this chapter, a sensitivity analysis was performed to quantify the level of uncertainty associated with each step of a water conservation process in order to provide realistic estimates of the speed and level of water use reduction in the Kingston distribution system described above. Kingston specific data was used to inform the parameter values wherever possible. Specifically, the water distribution system was provided by the city. The network model included all the pipe segments, pumps, storage tanks and flow/pressure control valves throughout the distribution system. The pump curves were provided for each pump and a global impeller-motor efficiency of 70% value was adopted from a published study that evaluated the average efficiencies of pumps throughout Ontario (Hydratek, 2013). The network system also included patterned nodal demands. The number of households, and the number of residents per household within each neighbourhood (defined in the section entitled Characterization of Neighbourhoods) was taken from census data (Government of Canada, 2011).
An agent-based model was created where agents represent households that use water through a water end-use model. A novelty afforded by using agents to represent households is their ability to interact with each other, enabling information to disseminate amongst a population causing agents to update their behaviours. The sensitivity analysis of the social network parameters presented in this work focuses on the underlying structure of communication between agents as communication was judged to be the starting point of any conservation or efficiency strategy. Word-of-mouth (from a marketing perspective) relates to individuals exchanging information or sharing their ideas about particular products or services (Chen et al. 2012). Ideas propagate through a population through communication strategies whether that communication happens between individuals or through some other medium (e.g. newspaper ads, radio ads, social media). The effect of the underlying structure of social networks and how that information is disseminated is what is being investigated through the sensitivity analysis. The rationale behind this approach was to determine the sensitivity of adoption rate to the underlying network parameters before adding complexity to the ABM that could better reflect the motivations of individuals purchasing water-efficient fixtures.

The ABM model makes use of a social communication network to simulate the diffusion of low-flow appliances amongst agents and to calculate the water reductions associated with the diffusion of these fixtures. The level of energy reduction associated with the water savings was determined with the use of the pipe network solver EPANET2 (Rossman, 2000), the break horsepower equation along with energy intensity values from treatment plants that serve the distribution system. The focus of the sensitivity analysis was on the social network ABM parameters that affect diffusion speed of the efficiency measure, the effectiveness of low-flow
fixtures in reducing water use and the sensitivity of energy use of the system with respect to water use.

*End-use model:* The fixture-level model of Blokker et al. (2010) in Equation [6] was used to quantify water use. The model was modified in that flow rates and durations are deterministic as opposed to probabilistic variables, however the frequency of use remain probabilistic. The total daily household demand was calculated by summing water uses from each household across a time step of one day

\[ Q = \sum_{k=1}^{M} \sum_{j=1}^{N} \sum_{i=1}^{F_{jk}} (I_{jk} D_{jk}) + \sum_{k=1}^{M} \sum_{j=1}^{N} \sum_{i=1}^{F_{jk}} (T_{jk} + L_{jk} + W_{jk} + B_{jk}) \]  

[6]

The flows per household \((Q)\) [L] were determined by calculating the flow of six indoor fixture categories within each household: toilets, taps, showers, washing machine, dish washer, bathtub and adding their contributions in order to evaluate total household demand. Shower and tap use was calculated by multiplying the duration \((D)\) [s] with the intensity \((I)\) [L/s] of end uses \((k)\) [fixture] from 1 to \(M\). This was repeated for the number of end users \((j)\) [persons] per house from 1 to \(N\) with the frequency \((i)\) [events/person] from 1 to \(F_{jk}\) from each user. The volume of water [L] used to flush toilets \((T)\) , and to operate laundry machines \((L)\), dishwashers \((W)\) and bathtubs \((B)\) were calculated using the frequency \((i)\) [events/day] from 1 to \(F_{jk}\) multiplied by the water use per event from each each end-user in the household. The frequencies consist of counts of the number of residents per house with values ranging between 1 and 6. The flows were determined by whether the appliances are low-flow or standard. Standard fixtures have higher flow rates than their low-flow counterparts. The model was used to create a population of household agents by drawing variates from frequency distribution functions. The distribution functions consisted of histograms of household occupancy of the Kingston neighbourhoods. A random number generator was used with specified seed values which ensured the same neighbourhoods were created for every simulation. The initialization was such that although individual household
attributes were estimated, although the distribution of household occupancy for each neighbourhood matched those provided by the census. This created groups of agents that represented specific Kingston neighbourhoods and considered heterogeneity amidst neighbourhoods with respect to household occupancy.

Appliance-use frequencies and durations: The model makes use of empirical probability density functions (PDF) to determine the frequency of use for each appliance given the number of people per household. In each simulated day, a random variate was drawn from the frequency-of-use PDF such that water-use was changed every day for the same household. The simulation was carried forth over one hundred time steps to calculate the average daily demand for each household. The number of time steps was chosen based on computational efficiency and low standard deviations for the final solutions (< 2% of final mean value). In the absence of any local frequency-of-use data, the cumulative frequency distributions developed by Sheepers (2012) with the Residential End Uses of Water Study (REUWS) database of indoor end-uses across 1,188 households in 14 cities in the US and Canada (Mayer et al., 1999) were used in this work. Indoor household water use was disaggregated into six fixtures as shown in Table 3.4.1. In this table, showers, toilets, laundry machines and dishwashers are either water-efficient (low-flow water use) or standard. These values categorize the fixtures by their flow intensities. Faucets have fixed flow intensities and were assigned constant durations. The reason that water efficient faucets were not included is because the flow rates of faucets are often partially open which makes the estimation of water savings difficult without physical measurements. This is also the case for showerheads however; showers are generally turned completely on while this is not necessarily the case for faucets. The proportion of hot-to-cold water for each fixture reported in DeOreo et al. (2016) was adopted such that 100% of water use for dishwashers was hot water, 59.1% of bath water, 57% of tap use, 20% of washing machine water use, and 66.2% of water used for showers.
Table 3.4.1: Standard water use, low-flow water use, duration, and frequency for household fixtures.

<table>
<thead>
<tr>
<th>Fixtures</th>
<th>Standard Water Use</th>
<th>Low Flow Water Use</th>
<th>Duration</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faucet¹</td>
<td>8.3 L/min</td>
<td>8.3 L/min</td>
<td>0.5 min/event²</td>
<td>CDF⁴</td>
</tr>
<tr>
<td>Bath²</td>
<td>75.0 L</td>
<td>75.0 L</td>
<td>-</td>
<td>CDF⁴</td>
</tr>
<tr>
<td>Shower⁵</td>
<td>17.1 L/min</td>
<td>9.5 L/min</td>
<td>7.8 min/event²</td>
<td>CDF⁴</td>
</tr>
<tr>
<td>Toilet¹</td>
<td>13.0 L/flush</td>
<td>4.8 L/flush</td>
<td>-</td>
<td>CDF⁴</td>
</tr>
<tr>
<td>Laundry³</td>
<td>87.0 L/load</td>
<td>49.2 L/load</td>
<td>-</td>
<td>CDF⁴</td>
</tr>
<tr>
<td>Dishwasher³</td>
<td>40.0 L/cycle</td>
<td>13.2 L/cycle</td>
<td>-</td>
<td>CDF⁴</td>
</tr>
</tbody>
</table>

¹ Alliance for Water Efficiency (2016)
² DeOreo et al. (2016)
³ Energy Star (2016)
⁴ Cumulative Density Function derived in Sheepers (2012)
⁵ Babooram & Hurst (2011)

The flow intensities were identical for every respective fixture type within the house. Although in reality, households can be equipped with a low-flow and standard appliances in cases where the household has multiple fixtures of the same type (e.g., regular toilet in upstairs bathroom and low-flow in basement), these distinctions are not made within the model. A household can reduce its water consumption by switching from a standard to a water-efficient fixture. The model “creates” homes with household attributes (low-flow and standard) fixtures based on initial penetration rates. The initial penetration rate refers to the fraction of the population that is already equipped with the water-efficient fixture. There are uncertainties associated with the parameters introduced in the end-use model. In reality, flow duration is not fixed and there exists a wide variety of water fixtures with unique flow rates. However, the differences in reported values are relatively small compared to the uncertainty associated with other elements of this framework. Both shower and tap use durations were taken from reported values in DeOreo et al. (2016) and were identical to those reported in Mayer et al. (1999). The results compared indoor water use for a population of houses with different water-efficient fixture penetration rates against a baseline scenario. The results are presented in terms of water savings based on lowering the flow rate for
specific fixtures. Values adopted for shower lengths and duration of tap use would therefore affect the total water savings however, the fraction of water that is being saved would remain the same.

**Word-of-mouth communication network:** Agents exert influence over each other through a social communication network. The influence mechanism is based on contagion, where the diffusion of innovation draws parallels with the spread of an epidemic (Young, 2009). This type of model is often used in marketing science to forecast product sales (Bass et al., 1994). The agents are connected with their neighbours through communication pathways which allows them to send and receive information from neighbours to whom they are connected. The information in this context is a signal to buy a certain low-flow fixture. There is considerable uncertainty in estimating how people are connected, and how receptive they are to being influenced by their friends and neighbours. There is scarce data available for this type social parameter which makes it difficult to estimate values for the ABM model. The sensitivity analysis was undertaken as a way to test the responsiveness of adoption rate given the social network parameters that govern speed of diffusion for low-flow fixtures. Since social networks have been found to exhibit properties of small-world graphs (Alkemade & Castaldi, 2005), a small-world graph was used to structure the communication pathways between household agents (Watts & Strogatz 1998). A small-world graph is comprised of nodes and pathways that connect nodes. The agents serve as nodes and the path lengths are dictated by a link factor and number of connections. Small-world graphs are characterized by short path lengths between connected nodes and a high degree of clustering of pathways between the nodes (Watts & Strogatz, 1998). The agent-based model was based on a number of key parameters that are described below.
Connections per agent: This global parameter refers to the number of connections specific to each agent. Information can only be transmitted through agents that are connected. An agent which has adopted a low-flow technology (adopter) can influence their neighbour(s) to adopt the low-flow technology. In each year, adopter agents send “messages” at random to other agents with whom they are connected to convince them to adopt the low-flow technology. If these other agents who receive the message have not yet adopted the low-flow technology, then this new information may convince them to adopt the low-flow technology.

Link factor: Households have a number of direct connections (determined by the connections per agent parameter) with their immediate neighbour(s) but some of these connections can also be “re-wired” as to be connected with other agents further away. The link factor determines the probability that a link will not be “re-wired” to other remote agents. A link factor of 0.0 represents a network with connections established at random while a link factor between 0.9 and 0.99 creates a small-world network whereby agents are mostly linked to their immediate agent neighbours.

Adoption probability: This parameter refers to the likelihood that an agent who receives a message from an adopter agent (agent who has already adopted a low-flow technology) will also adopt the low-flow technology. The adoption probability parameter represents the chance of adoption upon receipt of a message. In reality, this parameter is likely affected by a number of things such as whether rebates are offered for the fixtures, consumer attitudes, past experiences and socio-economic considerations. These considerations, although important, are beyond the scope of this analysis. The present analysis focuses on the relative influence of all word-of-mouth parameters as it relates to the adoption of new fixtures. This approach was taken in order to
understand the relative influence of each parameter before adding complexity to the agents in future work.

*Initial penetration rate*: The initial penetration rate represents the fraction of the population who have already adopted the low-flow technology at the start of the simulation.

### 3.5 Experimental Design

The experiments were separated into three sensitivity analyses (SAs). To begin, the parameters within the word-of-mouth communication network were tested. The communication network is comprised of five parameters (presented above). The household agents communicate with each other by prompting their neighbours to adopt a water saving fixture if they have done so themselves. The parameters that govern the communication network affect the speed at which the technology is diffused through the population. The sensitivity of water reductions to uncertainties in low-flow fixture adoption rates consisted of testing the level of water reductions that are achievable through the adoption of different water saving fixtures (low-flow showerheads, low-flow toilets, low-flow dishwashers and low-flow washing machines). In order to test this, a group of household agents were initialized as water consumers and the proportion of them that were equipped with low-flow fixtures was varied one by one.

Finally, the amount of energy reductions that were achieved through the water reductions found in the second sensitivity analysis was tested by calculating the energy requirements to deliver and treat the different levels of water demand. This following strategy was adopted given the fact that, although of all the elements within this framework are linked, the subset of parameters for each SA have different response variables. The social parameters used in the ABM model indirectly affect water use by influencing adoption rates. Adoption rates affect water use (to varying degrees depending on the fixture that is adopted) and finally, water use effects energy use. In this way the results from each SA informs parameter values that are used in subsequent SAs.
3.5.1 Sensitivity of Speed and Diffusion of Low-Flow Technologies to Uncertainties in Social ABM Parameters

A one-way sensitivity analysis was undertaken in order to measure the effect of the aforementioned social ABM parameters on the adoption rate of low-flow fixtures. The level of uncertainty in these parameters were judged to be high compared to those presented in the end-use model and as such were determined to be good candidates for a sensitivity analysis. Table 3.4.1 indicates the parameters considered in the sensitivity analysis as well as the minimum, maximum, and base values used in the analysis. Due to the stochastic nature of the model, one hundred iterations were performed for each simulation run. The results presented in the following sub-sections represent the mean and standard deviation of those one hundred iterations. Run lengths of 5, 10, 15 and 20 years were undertaken in order to capture the speed of diffusion and to represent realistic timelines for the implementation of conservation strategies. The initial penetration rate of a low-flow fixture values were varied from 10 percent to 70 percent based on results presented by Babooram & Hurst (2011) and DeOreo et al. (2016) who examined the penetration rates of low-flow fixtures in North American cities. The number of households were modeled on the size of neighbourhoods based on the aforementioned Statistics Canada census (City of Kingston, 2008). The link factor was varied for typical values for small-world graphs (Watts & Strogatz, 1998) as indicated in Table 2. No prior information on the probability of adoption or the connections per agents parameter was available, therefore a wide range of values were analyzed. For the probability of adoption parameter, the lower bound was chosen so that at the end of the 20-year simulation, no agents had adopted the technology while the upper bound was chosen so that every agent had adopted the technology after the 5-year simulation period.
Table 3.5.1: Sensitivity analysis parameters for diffusion, adoption rates, water reduction, energy use.

<table>
<thead>
<tr>
<th>Category</th>
<th>Variables (units)</th>
<th>Min.</th>
<th>Max.</th>
<th>Base Value</th>
<th>Sources</th>
<th>Response variable</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social parameters</td>
<td>Probability of adoption (probability)</td>
<td>0.01</td>
<td>0.4</td>
<td>0.05</td>
<td></td>
<td>L-F fixture</td>
<td>How do social and network parameters affect the speed and diffusion (adoption rates) of low-flow technology?</td>
</tr>
<tr>
<td></td>
<td>Connections per agent (connections)</td>
<td>1</td>
<td>20</td>
<td>4</td>
<td>[1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Link factor (probability)</td>
<td>0.9</td>
<td>0.99</td>
<td>0.95</td>
<td>[1]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td># of households</td>
<td>500</td>
<td>3000</td>
<td>2000</td>
<td>[2]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial penetration rate (percentage)</td>
<td>0.1</td>
<td>0.7</td>
<td>0.4</td>
<td>[3],[4]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-F Fixture adoption rate</td>
<td>L-F™ showers (percentage)</td>
<td>70</td>
<td>100</td>
<td>70</td>
<td>[3]</td>
<td>Water reductions</td>
<td>How effective are low-flow fixtures at reducing water-use?</td>
</tr>
<tr>
<td></td>
<td>L-F™ toilets (percentage)</td>
<td>40</td>
<td>100</td>
<td>40</td>
<td>[3,4]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L-F™ washing machine (percentage)</td>
<td>70</td>
<td>100</td>
<td>70</td>
<td>[5]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L-F™ dishwasher (percentage)</td>
<td>90</td>
<td>100</td>
<td>90</td>
<td>[5]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of households (percentage)</td>
<td></td>
<td></td>
<td>2000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Reductions</td>
<td>Indoor water reduction (percentage)</td>
<td>5</td>
<td>18</td>
<td>0</td>
<td>-</td>
<td>Energy-Use</td>
<td>How sensitive is energy-use to water reductions?</td>
</tr>
</tbody>
</table>

†Low-flow

3.5.2 Sensitivity of Water Reductions to Uncertainties in Low-Flow Fixture Adoption Rates

The potential for indoor water reduction was evaluated given increased adoption of four specific water-saving fixtures: toilets, showers, washing machines and dishwashers. Three adoption scenarios were examined. The first two scenarios consisted of varying adoption rates for each fixture within a neighbourhood of two thousand residents, while the third scenario varied adoption rates throughout the entire city. The distribution of household occupancy for the first two scenarios was taken from a residential neighbourhood in Kingston where the occupancy in the majority of the houses was between 2 and 4 people. In the first two scenarios, adoption rates were varied from a baseline where a percentage of households were already equipped with water-efficient fixtures at the outset; total water and hot water reductions were evaluated respectively. Existing penetration rates for low-flow fixtures for the neighbourhood were based on those reported by Babooram & Hurst (2011) for water-saving showers and toilets and penetration rates reported by Natural Resources Canada (2013) for low-flow dishwashers and washing machines (Table 3.5.1). A third scenario was examined in which all households in the City of Kingston adopted low-flow showers, toilets, washing machines, and dishwashers to evaluate the theoretical maximum potential in water reduction achievable in Kingston.

3.5.3 Sensitivity of Energy Reductions

The ABM in combination with a geographic information system (QGIS Development Team, 2016) were used to set the water demands in specific geographic locations (neighbourhoods) within the hydraulic model of the City of Kingston distribution system. The hydraulic solver EPANET2 (Rossman, 2000) was used to calculate the discharge and pumping heads at the pumps of the system in response to the water demands established with the ABM in the Kingston distribution system.

Burn-in simulations were run with the EPANET2 (Rossman 2000) hydraulic model over a 31-day period with a 1-hour time step and daily average energy use was calculated based on the results.
The daily average energy use was multiplied by 365 days in order to calculate annual energy usage. The 31-day period was chosen to allow all tanks in the system to undergo several drain and fill cycles. A representative average pump efficiency ($\eta$) of 70 percent was adopted for every pump in the system (Hydratek, 2013). The EPANET2 hydraulic model was run to calculate the pumping head [m] ($H$) and pump discharge [m³/s] ($Q$) for each pump ($P$) to evaluate the brake horsepower equation (7) with the unit weight of water [$\gamma = 9.81 \text{kN/m}^3$] and determine the energy use in the system.

$$W_{p,t} = \gamma \sum_{i=1}^{P} \frac{Q_{p,i} H_{i,t}}{\eta}$$ \hspace{1cm} [7]

$$E_p = W_p = \sum_{t=0}^{T} W_{p,t} \cdot \Delta t$$ \hspace{1cm} [8]

The energy use in the system [kWh], $E_p$, was calculated by integrating the power $W_{p,t}$ to transport water [kJ/s] and maintain adequate pressures using the brake horsepower equation [7] over the time step (s) $\Delta t$ from $t = 0$ to $t = T$ across the $i = 1, 2, \ldots, P$ pumps in the system. Energy requirements for treating the water at the two treatment plants were determined from data provided by Utilities Kingston and set to 270.5 kWh/ML for the King Street water treatment plant and 425.7 kWh/ML for the Point Pleasant water treatment plant (Utilities Kingston, 2015).

### 3.6 Results

#### 3.6.1 Sensitivity of Adoption Rate to Social Network Parameters

The change in adoption rate was found to be sensitive to three out of five parameters tested, namely, adoption probability, connections per agents, and initial penetration rate for the range of values chosen. Changing the number of households or the link factor within the system had no effect on the change in adoption rate for any of the time periods tested. The adoption probability parameter had the largest impact on determining the speed of diffusion of low-flow fixtures, followed by the initial penetration rate and finally the connections per agent. The following section presents the mean values for each scenario along with their standard deviations.
3.6.2 Sensitivity of Adoption Rate to Adoption Probability

Adoption probability was found to be the most important factor that drives adoption rate. The results reported in Figure 3.6.1 show the change in adoption rate given different levels of adoption probability from an initial 40% penetration rate. Results are grouped together by simulation lengths ranging from 5 to 20 years. The adoption probability represents the probability that an agent will adopt a low-flow fixture upon receiving a favorable message from an adopter. An adoption probability of 10% represents a 10% probability that an agent will adopt the use of a low-flow fixture when contacted by an adopter agent. For the 5-year simulation time frame, the change in adoption rate varied from 1 ± 1% to 38 ± 1% when the lowest (1%) and highest (40%) adoption probability parameters were adopted. This indicates that when the probability of adoption is low enough, there may not actually be an increased adoption given the variability of results produced in each simulation run. Figure 3.6.1 shows that, with an adoption probability of 40%, the change in adoption rate is 60% for a 20-year simulation length. Given the initial penetration rate of 40% the entire neighbourhood population (100%) would adopt a low-flow fixture after 20 years. When the adoption probability parameter was set to 20% and 30%, for the same 20-year period, market saturation was almost reached with increase in adoption rates of 53 ± 1% and 58 ± 1%, respectively.
3.6.3 Sensitivity of Adoption Rate to Initial Penetration Rate

The results in Figure 3.6.2 suggest that increasing the adoption rate of low-flow fixtures was most effective for initial penetration rates near 50% and less effective for initial penetration rates much higher or lower than 50%. This trend was found to be consistent for every simulation length. As an example, the results in Figure 3.6.2 show that at time $t = 15$ years, initial penetration rates ranging between 40% and 50% produced the highest adoption rates of approximately $17 \pm 1\%$. As a point of comparison, initial penetration rates of 20% and 70% both produced a change in adoption rate of $13 \pm 1\%$ at time $t = 15$ years.
Figure 3.6.2: Mean change in adoption rate at times $t = 5$ years, $t = 10$ years, $t = 15$ years, and $t = 20$ years for initial penetration rates of 10 percent, 20 percent, 30 percent, 40 percent, 50 percent, 60 percent and 70 percent. Error bars show standard deviation.

3.6.4 Sensitivity of Adoption Rate to Connections Per Agent

The results in Table 3.6.1 suggest that the number of connections per agent had little effect on the change in adoption rate observed at all times. The results in Table 3.6.1 indicate that over a 20-year period, adoption rate could increase from an original 40% penetration rate by $15 \pm 1\%$ if the agents were connected to 1 other agent or by $24 \pm 1\%$ if the agents were connected with 20 other agents. If agents are highly connected, there is an increased chance that potential adopters will receive a message from an adopter since there are more communication channels available for message transmission.
Table 3.6.1: Change in adoption rate versus number of connections per agent. All values given in percentages, numbers in parentheses represent standard deviation.

<table>
<thead>
<tr>
<th>Connections Per Agent (No. of Connections)</th>
<th>5 years</th>
<th>10 years</th>
<th>15 years</th>
<th>20 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Change in adoption rate (All values in %)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6 (± 1)</td>
<td>9 (± 1)</td>
<td>12 (± 1)</td>
<td>15 (± 1)</td>
</tr>
<tr>
<td>2</td>
<td>6 (± 1)</td>
<td>11 (± 1)</td>
<td>15 (± 1)</td>
<td>19 (± 2)</td>
</tr>
<tr>
<td>3</td>
<td>6 (± 1)</td>
<td>11 (± 1)</td>
<td>16 (± 1)</td>
<td>21 (± 1)</td>
</tr>
<tr>
<td>4</td>
<td>6 (± 1)</td>
<td>11 (± 1)</td>
<td>17 (± 1)</td>
<td>22 (± 2)</td>
</tr>
<tr>
<td>5</td>
<td>6 (± 1)</td>
<td>12 (± 1)</td>
<td>17 (± 1)</td>
<td>22 (± 2)</td>
</tr>
<tr>
<td>10</td>
<td>6 (± 1)</td>
<td>12 (± 1)</td>
<td>18 (± 1)</td>
<td>24 (± 1)</td>
</tr>
<tr>
<td>15</td>
<td>6 (± 1)</td>
<td>12 (± 1)</td>
<td>18 (± 1)</td>
<td>24 (± 1)</td>
</tr>
<tr>
<td>20</td>
<td>6 (± 1)</td>
<td>12 (± 1)</td>
<td>18 (± 1)</td>
<td>24 (± 2)</td>
</tr>
</tbody>
</table>

3.6.5 Water reductions Achievable through increasing the Penetration Rate of Water-Efficient Fixtures

Figure 3.6.3 presents water reductions of indoor water use relative to the baseline scenario in which a neighbourhood has an initial penetration rate of 40% of low-flow toilets, 70% low-flow showers and washing machines as well as 90% initial penetration rate for low-flow dishwashers at simulation time $t = 0$. These initial penetrations are estimates of the actual initial penetration rates of the respective fixtures in the City of Kingston based on studies in similar North American cities (Babooram & Hurst, 2011). The results in Figure 3.6.3 suggest that low-flow toilets are most effective at reducing water use compared to the other three fixtures tested. Part of this result stems from the fact that there are fewer households equipped with this technology compared to the other fixtures modeled. The results also show that the complete adoption of low-flow toilets (penetration rate of 100% in Figure 3.6.3) produces a $9 ± 1\%$ reduction in indoor water use. Further, the complete adoption of low-flow showers produces a $5 ± 1\%$ reduction in indoor water use, while the complete adoption of efficient washing machines and efficient dishwashers produce reductions of $3 ± 1\%$ and $0 ± 1\%$ in indoor water use respectively.
Mean indoor water reductions (in percent) relative to base scenario with initial penetration rates versus varying low-flow fixture penetration rates (toilets, showers; washing machines and dishwashers) for a neighbourhood in the City of Kingston. (Initial penetration rate set to 40 percent for low-flow toilets, 70 percent for low-flow showers, 70 percent for low-flow washing machines, 90 percent for low-flow dishwashers.) Error bars show standard deviation. Standard deviations that show negative water savings indicate that a portion of the results had mean water use higher than the mean of the base scenario.

The complete adoption of all four water-efficient fixtures could produce an $18 \pm 1\%$ reduction of indoor water use in the neighbourhood. Showers, washing machines and dishwashers use a mixture of hot and cold water. Figure 3.6.4 presents the percentage of hot water that can be saved through the increased adoption of water efficient showers, washing machines and dishwashers. The results are presented relative to initial hot water use for the neighbourhood. High efficiency showerheads produced the greatest level of hot water savings with up to $8 \pm 1\%$ of hot water savings found to be achievable by increasing the total adoption rate from the current estimated value of 70% to 100%. Dishwashers had an initial penetration rate of 90%, increasing that amount to 100% only produced hot water savings of $1 \pm 1\%$. 
Figure 3.6.4: Mean indoor hot water reductions (in percent) relative to base scenario with initial penetration rates versus varying low-flow fixture penetration rates (showers, washing machines and dishwashers) for a neighbourhood in the City of Kingston. (Initial penetration rate set to 40 percent for low-flow toilets, 70 percent for low-flow showers, 70 percent for low-flow washing machines, 90 percent for low-flow dishwashers.) Error bars show standard deviation. Standard deviations that show negative water savings indicate that a portion of the results had mean water use higher than the mean of the base scenario.

3.6.6 Total Potential Water Reductions for the City of Kingston

Each neighbourhood in the City of Kingston (40 neighbourhoods) was modeled with their respective number of households as well as distribution of household occupancy. Scenarios were run where the initial penetration rates of low-flow fixtures presented were identical to the previous scenario (partial penetration rate of water efficient-fixtures) and subsequently, with full adoption (100 percent adoption rate) of each low-flow fixture. This was undertaken in order to determine the potential water reduction for each neighbourhood as well potential savings for the entire city. The indoor water reduction potential was found to be 18 ± 1% for the majority of neighbourhoods (30 neighbourhoods); one neighbourhood experienced an indoor water reduction of 17 ± 1% and nine other neighbourhoods experienced a 19 ± 1% reduction. A total of an 18 ±
1% reduction in indoor water use was calculated for the entire Kingston distribution system. In total, indoor residential water demand was determined to be 51 ± 1% of total water demand in the Kingston distribution system. Given that indoor water demand is roughly half of total water use, an 18 ± 1% reduction in indoor water use corresponds to a 9 ± 1% reduction in total water use that can be achieved through market saturation of indoor fixture water saving devices.

### 3.6.7 Sensitivity of Pumping and Treatment Energy to Reductions in Water Use

The results in Table 3.6.2 present the level of energy reductions that could be achieved through various levels of indoor water savings (found to be achievable through the previous sensitivity analysis). Table 3.6.2 shows that reducing water use produces reductions in energy use that is approximately proportional to water savings. Specifically, a 5% reduction in indoor water use produced a 3% reduction in pumping energy in the system while an 18% reduction in indoor water use produced a 9% reduction in energy needed to treat and pump the water through the system.

<table>
<thead>
<tr>
<th>Change in total indoor water use</th>
<th>Water Use in Kingston System (ML/day)</th>
<th>Total energy use (kWh/day)</th>
<th>Change in Energy from Pumping and Water Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Reduction</td>
<td>69.0</td>
<td>41,071</td>
<td></td>
</tr>
<tr>
<td>-5%</td>
<td>67.0</td>
<td>39,942</td>
<td>-3%</td>
</tr>
<tr>
<td>-10%</td>
<td>66.2</td>
<td>39,289</td>
<td>-4%</td>
</tr>
<tr>
<td>-15%</td>
<td>63.9</td>
<td>37,962</td>
<td>-8%</td>
</tr>
<tr>
<td>-18%</td>
<td>62.9</td>
<td>37,398</td>
<td>-9%</td>
</tr>
</tbody>
</table>

### 3.7 Discussion

The results provide insights into the potential for reducing indoor water use through the adoption of low-flow fixtures as well as the sensitivity of the adoption of these water-efficient technologies to social parameters within an ABM diffusion model. The increase in adoption rate was found to
be sensitive to three out of the five social parameters of the ABM. Unsurprisingly, adoption probability was found to be the main driver of technology diffusion. If agents are more likely to adopt when they receive a message from adopters, the technology will be diffused more quickly throughout the population. The initial penetration rate of the fixtures was also found to influence how quickly the fixtures are adopted. This stems from the fact that the social communication network encoded in the ABM is based on contagion. For contagion models, the cumulative adoption graph creates a characteristic s-shape where a new technology diffuses slowly at the beginning when only a small portion of the population has adopted the technology in question (Lilien et al., 2007). Technology diffusion tends to slow considerably after a large portion of the population has adopted the technology as well, explained by the fact that there are fewer households able and willing to adopt the new technology.

Comparatively, the structure of connections within the social network had a much smaller effect on how quickly the water-efficient technologies were adopted. While the number of connections per agent did affect the results, the connection pattern which is governed by the link factor did not. Increasing the number of connections an adopter agent has increases the chance that, when the agent sends a message, it will be received by a potential adopter. The agents equipped with low-flow fixtures at the outset were randomized and therefore the likelihood of an adopter agent being connected with a potential adopter agent did not change on the basis of their connections. Although all of these parameters have a high level of uncertainty, the results of the sensitivity analysis suggest that water utilities should focus on estimating the adoption probability and the initial penetration rates as adoption rates are most sensitive to these parameters. This result is important from a modelling perspective. The connections per agent and link factor are parameters that are difficult to empirically measure. The implication is that, if the adoption rates would have been found to be sensitive to these parameters, the eventual calibration of this network structure
would be prohibitive. On the other hand, adoption probability and initial penetration rate can be estimated through household surveys. With the growth in data collection, there may be an opportunity to monitor the effectiveness of conservation campaigns particularly through the use of user feedback and social media. Data could be gathered which could then further inform assumptions about social behaviour and adoption probability.

While the City of Kingston has been pro-active at seeking water and energy efficiencies through infrastructure improvements and campaigns aimed at the commercial/institutional sector, absent from their strategy have been campaigns that target or encourage residential homes to adopt more efficient fixtures. The City of Kingston has taken steps to reduce water and water related energy use in the next 5 years (2014-2019) through operational efficiencies such as leak detection, pump upgrades and the separation of combined sewers (City of Kingston, 2014). To date, the only steps taken by the City to increase the adoption of efficient fixtures include: 1) a financial incentive program for multi-residential properties that includes offering a rebate to landlords for purchasing low-flow toilets, 2) an incentive program that offers $5 per cubic meter of annual water savings for commercial users and up to 20% of project costs for achieving these savings.

The results presented in the sensitivity analyses show the level of water savings that could be achieved through various adoption levels of water-efficient fixtures. The level of hot water savings was also shown and is a good proxy for energy savings related to water heating. A number of key features within the framework are particularly useful for modelling the energy-water relationship for residential customers. Including census data on a neighbourhood basis enabled water use to be modeled heterogeneously for the different neighbourhoods. The physical properties of the neighbourhoods such as spatial layout and distance from the source was also accounted for meaning that the water savings were site specific. Although average energy
intensities were used in order to calculate the energy requirements for water treatment, the two
treatment plants for this distribution system had very different energy intensities (270.5 kWh/ML
for the King street treatment plant and 425.7 kWh/ML for the Point Pleasant treatment plant). The
water reductions were specific to indoor households and the geographic locations of the water
savings were accounted for within the hydraulic model therefore water reductions to households
that were serviced by the King Street Treatment plant could result in greater energy savings.
These features could increase the accuracy of estimating energy savings through the distribution
network. The results indicate that the City of Kingston could have an opportunity to reduce their
water and energy use within their distribution system through a campaign aimed at encouraging
residents to adopt water-efficient fixtures and that this could lead to substantial energy savings.
The social connection network among agents was based on spatial proximity amongst agents in
that household agents were connected mostly with their neighbors. With the advent of
technology, widespread use of the internet and social media, the configuration of network
connexions may have changed from those proposed by the Wattz & Strogatz (1998) small-world
network algorithm. Using a spatial approach to network connections also excludes other
determinants that may affect how social networks are structured. Mcpherson et al (2011) put forth
that social network ties are governed by a variety of factors including ethnicity, age education and
workplace among others. The authors (McPherson et al., 2001) suggest that people tend to
interact with similar people a concept termed homophily. This concept has been used in
epidemiology research to study the role that social networks play in health and the spread of
diseases (Douglas et al., 2007). The agent connections created by the model were given equal
weighting in that receiving messages from any agent connection would prompt agents to consider
approach to account for the fact that ties between individuals may be stronger than others and
therefore social influence is not necessarily homogeneous among connections. Introducing a
greater degree of heterogeneity among agents in order to account for socio-economic characteristics of agents and have those characteristics play a role in governing their connections may be a more realistic approach and is suggested as an avenue for further research.

Parameter values that were specific to Kingston were adopted for the water and energy sensitivity analyses whenever data was available. However, given the absence of local data in some areas, published values of similar cities were adopted for a number of parameters. The absence of local data, particularly on the pervasiveness of adoption rates on specific water saving fixtures, limits the extent to which conclusions can be drawn about the water saving potential within the Kingston system. The sensitivity approach that was adopted for this work was undertaken in order to showcase a range of potential water/energy savings that could be achieved through different levels of water reductions in order to account for this shortcoming. The model also assumed that when a household replaced a fixture from standard to low-flow, every fixture of that type within the household would be replaced. In reality, people would likely change only one showerhead or toilet at a time and not necessarily all at once. Given this, the results may lead to an overestimation or realistic water savings. Fixture efficiencies also change in time therefore potential water savings would change in time as fixtures improve. Wastewater treatment and conveyance is another area of the urban water system that requires large amounts of energy to operate. The potential energy savings for these operations were not included in this work although they would also be of interest to municipalities. Kingston has a large number of combined sewers which would make these energy savings difficult to estimate. The results corroborated with previous studies that have shown energy use from pumping operations to be directly linked to water use (deMonsabert & Liner, 1998; Santosh R & Barkdoll, 2010). The results of this chapter established how those water reductions can be achieved through the adoption of water efficient fixtures, and estimated the level of participation for a fixture adoption
campaign that would be required to attain those levels of water reductions within the Kingston distribution system.

3.7.1 Future Work
The basis for the current chapter was to test the sensitivity of the social parameters that underlie a small-world network structure and the extent to which it affects water and energy use. Although social pressure has been found to influence water saving behaviour (Jorgensen et al., 2009; Walton & Hume, 2011; Sauri, 2013; Koutiva et al., 2017), there are a variety of other factors that influence individual actions as well. In reality, additional factors such as home ownership status, attitudes towards conservation, price and whether water use is metered are all variables that have also been shown to correlate with the adoption of water-efficient fixtures (Millock & Nauges, 2010). These additional variables have not been included in the ABM used in this chapter to simulate the interactions between water customers. Future work in this area would benefit from a cross-disciplinary approach that could include interviews and surveys that seek to understand the individual motivations, and how they affect adoption probability and thus help improve the realism of ABM models.

3.8 Summary and Conclusions
This chapter presented the results of a sensitivity analysis that examined the impact of human social interactions (as modelled with an agent-based model) on water and energy use in the Kingston water distribution system in eastern Ontario, Canada. Three ABM parameters were found to have an important impact on the adoption of low-flow fixtures, namely adoption probability, initial penetration rates, and connections per agent. Low-flow toilets, low-flow showers, and water efficient washing machines and dishwashers were estimated to have the potential to reduce water use (9 percent) and energy used for treating and pumping water (9 percent) within the Kingston distribution system. The results suggest that fixture replacement
campaigns have the potential to reduce water and energy use in distribution systems even though many households already make use of low-flow fixtures.

3.9 References


http://www.allianceforwaterefficiency.org/toilet_fixtures.aspx


http://www.allianceforwaterefficiency.org/Faucet_Fixtures_Introduction.aspx


Government of Canada.


Chapter 4

Simulating Geographically Targeted Conservation Strategies Using an Agent-Based Model: Water and Energy Implications for a Mid-Sized Canadian City

4.1 Abstract

This chapter examines to what extent geographically-targeted conservation strategies can reduce water use and energy use in a water distribution system and proposes a method of modelling communication strategies that promote water saving. A new modelling approach was developed that coupled an agent-based with the hydraulic network solver to simulate the achievable water and energy savings from targeted water conservation and efficiency campaigns in specific regions of the water distribution system in Kingston, Ontario, Canada. An illustrative case study is developed in which Kingston inhabitants are represented as household agent water users in an agent-based model. The unique approach incorporates modelling the communication strategies that can be used to promote water reduction measures to the public. The case study involved simulating a mail-in and social media campaign and estimating the timelines required for the agents to participate in the program. Different areas of the distribution network were then targeted with an efficiency campaign of retrofitting households with water efficient fixtures in order to test whether there are any advantages in terms of energy savings for targeting specific areas within the system. The results showed that energy reductions varied slightly depending on where the water reductions were located however implementing a conservation or efficiency campaign in localized areas could take much longer to recruit an equal number of participants than a non-targeted campaign.
4.2 Introduction

Canada’s drinking water infrastructure is aging. In Ontario (Canada’s most populous province), decades of underinvestment have led to an infrastructure deficit in the water sector (Fenn & Kitchen, 2016). In some cases, demand-side management can be used to increase the efficiency of infrastructure by lowering the cost of treatment and by reducing pumping requirements (Sahely & Kennedy, 2007). This is especially true for North American cities given their high rates of per capita water use. Some Canadian municipalities are using water conservation and efficiency campaigns aimed at the residential sector in order to reduce water use (Waller & Scott, 1998). Typical demand management strategies aimed at the residential sector include policy changes such as watering restrictions, price adjustments or technological changes. Technological strategies can include equipping homes with more water-efficient fixtures, utilizing water re-use schemes such as water recycling and rain barrels or modifying a fixture to eliminate the need for water altogether (compost toilets).

Water is delivered to customers via water distribution networks that comprise looped pressurized pipes that convey water from source to tap above prescribed minimum pressures. Pumps are used to add mechanical energy to pressurize the water and convey it to the end-user while overcoming friction losses and elevation differences. Previous research has established that network layout, topology and spatial distribution of water withdrawals influences the amount of energy that must be added to a system (Pelli & Hitz, 2000; Spang & Loge 2015). Considering this, the implementation of water conservation campaigns in specific locations to target water reductions in those locations could play a role in determining the amount of energy savings associated with those region-specific water reductions. It thus stands to reason that planners could target water reductions in specific areas of the distribution system to maximize energy savings. In order to target specific groups to (potentially) maximise energy savings, conservation campaigns must be
tailored to the area of interest. This however, would represent a change in strategy in that the number of residents that are targeted would be limited to a certain geographic location as opposed to the community at large. The chapter builds on the model developed in chapter 3 and exploits the ABM model features to examine whether the spatial distribution of water savings has an important effect on energy reductions associated with pumping operations in a water distribution system.

Three features of the ABM that were particularly compelling for water/energy conservation modelling were: i) the water conservation campaigns were implemented in specific areas of the distribution system and therefore water use and energy use reductions could be attributed to the region-specific conservation campaigns, ii) the water reductions were attributable to specific fixtures and, iii) the social communication and the diffusion of information was modeled which enabled the creation of scenarios to simulate communication strategies.

The aim of this chapter was to examine to what extent geographically-targeted conservation strategies can reduce water use and energy use in a water distribution system and to present a new methodology that simulates the implementation of communication strategies meant to promote water saving measures. The ABM developed in Chapter 3 was modified and coupled with a hydraulic network model used to simulate region-specific water conservation campaigns and their impact on the water and energy use in the Kingston distribution system. A communication strategy was then modeled using agents to produce estimates of adoption timelines for geographically-targeted water reduction measures.

**4.3 Agent-Based Modelling Approach**

Two separate, but related, set of experiments were created in order to examine how the spatial distribution of water savings affects energy use in the Kingston system and to model
communication strategies that would lead to users adopting the water saving measures. The first set of experiments examined the timelines for which a conservation plan could realistically be achieved given a specific communication strategy implemented within two populations of different sizes. A communication strategy refers to an approach that conservation officers can use to inform the public of a particular water saving campaign. The second set of experiments was designed to measure the energy reductions associated with water savings achieved in various geographic locations throughout the Kingston distribution system. A collection of neighbourhoods was grouped together based on geographic location and were targeted with the water conservation campaign. Specific locations were targeted with an identical conservation strategy in order to test whether water reductions in certain areas offered greater energy savings than others. The ABM developed in Chapter 3 was used in order simulate a communication strategy, first on small neighbourhood cluster of 6000 household agents and subsequently on the entire city of Kingston as a mean to compare the potential trade-offs of targeting smaller group sizes. A conservation target was then created, and the localized water savings were evaluated through the use of the water distribution hydraulic network model EPANET2 (Rossman 2000) for the City of Kingston in order to determine the energy reductions associated with the conservation measures. The following section describes the ABM used to model household water use within Kingston followed by the experimental design. The model consists of a collection of “agents” that represent household water users. A conservation agent communicates specific conservation strategies to the household agents which encourage them to participate in a water saving campaign. Subsequently, three unique locations were targeted within Kingston in order to test whether water reductions in certain areas offer greater energy savings than others.

The agent-based model presented in the previous chapter is a collection of agents that represent household water users. The ABM calculates water use through the use of an end use model that
evaluates water use by disaggregating indoor household water demand into six indoor water fixtures: toilet, bathtub, shower, washing machine and dishwasher. The SIMEDEUM model (Blokker et al, 2010) was used where indoor household water consumption is calculated by summing the flow contributions of each fixture. The product of intensity [l/s], duration [s], frequency [events] for shower use and tap use was summed for every household and the product of frequency and water use per event [l] was calculated for the remaining fixtures. The SIMEDEUM model was modified in that duration and flow rates for the fixtures were deterministic rather than stochastic variables. Four fixtures within the model were either low-flow or standard: toilets, showers, washing machines and dishwashers, the distinction determined the specific flow rate of each of these fixtures within the households. Table 4.3.1 summarizes the parameters for the end-use model. The frequency in which these appliances were used by a specific household was evaluated through the use of empirically derived probability distributions functions (PDFs). Each fixture had a frequency-of-use function associated with its use. The frequency-of-use distributions varied depending on the household occupancy. In the absence of local data, the frequency distributions presented by Sheepers (2012) derived from empirical data (Mayer et al. 1999) were used. The data consists of frequency-of-use histograms of household appliances that were measured with data loggers installed in 1,118 households located in the US and Canada (Mayer et al. 1999). The number of agent households and their occupancy matched the population of Kingston taken from census data (Statistics Canada, 2015) described in a following section. The census data was grouped in terms of neighbourhoods that represent a few street blocks. This made it possible to estimate the distribution of household occupancy throughout every neighbourhood in Kingston. The household agents were grouped into the same neighbourhoods as per the census data mentioned above and were linked to the hydraulic network solver EPANET2 (Rossman, 2000) by associating a subset of model nodes in close proximity to the households. Two agent types were created in the model: 1) household agents; and 2) a
conservation agent. A communication structure was embedded within the ABM that enabled the spread of information between agents. The conservation agent communicated specific conservation strategies to the household agents which encouraged them to participate in a conservation campaign. The household agents were endowed with the ability to transmit information with other household agents to whom they were connected. Each household agent was connected with two other household agents. Social networks have found to exhibit properties of small-world graphs (Alkemade & Castaldi, 2005) and for this reason, a small world graph structure was used to govern to whom the agents were connected. One hundred iterations of daily water use were recorded in order to capture the variability of water use and water savings on any given day.

Table 4.3.1 Standard water use, low-flow water use, duration, and frequency for household fixtures (Tourigny & Filion, 2017).

<table>
<thead>
<tr>
<th>Fixtures</th>
<th>Standard Water Use</th>
<th>Low Flow Water Use</th>
<th>Duration</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faucet^1</td>
<td>8.3 L/min</td>
<td>8.3 L/min</td>
<td>0.5 min/event^2</td>
<td>CDF^4</td>
</tr>
<tr>
<td>Bath^2</td>
<td>75.0 L</td>
<td>75.0 L</td>
<td>-</td>
<td>CDF^4</td>
</tr>
<tr>
<td>Shower^1</td>
<td>17.1 L/min</td>
<td>9.5 L/min</td>
<td>7.8 min/event^2</td>
<td>CDF^4</td>
</tr>
<tr>
<td>Toilet^1</td>
<td>13.0 L/flush</td>
<td>4.8 L/flush</td>
<td>-</td>
<td>CDF^4</td>
</tr>
<tr>
<td>Laundry^3</td>
<td>87.0 L/load</td>
<td>49.2 L/load</td>
<td>-</td>
<td>CDF^4</td>
</tr>
<tr>
<td>Dishwasher^3</td>
<td>40.0 L/cycle</td>
<td>13.2 L/cycle</td>
<td>-</td>
<td>CDF^4</td>
</tr>
</tbody>
</table>

^1 Alliance for Water Efficiency (2016)
^2 DeOreo et al. (2016)
^3 Energy Star (2016)
^4 Cumulative Density Function derived in Sheepers (2012)

4.4 Kingston Distribution System (Test City)

The City of Kingston is located in southeastern Ontario Canada, on the eastern edge of Lake Ontario and the St-Lawrence River. The water and wastewater works are owned by the City but privately operated by Utilities Kingston. The Kingston water distribution system includes 5 booster stations, 561 km of water mains and 11 storage facilities (Utilities Kingston, 2015). In
order to segment the population of Kingston into relatively homogenous groups to target for specific conservation measures, neighbourhood profiles from the 2011 Statistics Canada census were used (Statistics Canada, 2015). The census distinguishes 43 separate neighbourhoods throughout the city limits based on geographic location. The census data (Statistics Canada, 2015) was used to obtain information on residential housing statistics within each neighbourhood. Each neighbourhood represents 5 to 7 street blocks where each block contains between 500 and 700 residential dwellings. The statistics drawn from the data were used to create neighbourhoods of household agents with a matching number of households and distribution of household occupancy.

4.5 Experimental Design
The experimental design was created in order to demonstrate the use of the ABM model in simulating both a communication strategy together with the potential water and energy savings associated with the adoption of low-flow fixtures within various areas of Kingston. Two separate types of experiments were created to achieve this. The first set of experiments were termed communication scenarios which consisted of simulating a set of communication strategies for two separate campaigns. The first campaign modeled a fixture rebate program while the second campaign modeled a conservation campaign that would target water consumption behaviours. The decision structure embedded in the agents is shown on Figure 4.5.1 and was identical for both campaigns, save for different parameter values. The simulations were run in order to estimate a timeframe for the efficiency and conservation campaigns to reach different participation levels of household agents. The second set of experiments examined whether the geographic location of water conservation programs had an impact on achievable energy savings in the Kingston distribution system. Four scenarios were compared in order to test the effect of targeted water reductions against a baseline case where no conservation measures were put in place.
4.5.1 Communication Scenarios

A communication strategy meant to promote the conservation and efficiency campaigns were modeled using the ABM, a summary of the scenarios is presented in Figure 4.5.2. The communication strategy was tested on two different target populations: a cluster of 6000 household agents which represented a subset of the Kingston population referred to as a “targeted group” and a larger “non-targeted group” comprised of all of the Kingston households serviced by the distribution system. The communication strategy consisted of targeting individual household agents by combining two communication approaches. The first communication approach used inter-agent communication to simulate a mail-in leaflet campaign while the second communication approach used inter-agent communication to model a social media campaign. For the social media communication approach, agents were prompted to participate in the campaign and subsequently share the action with the agents with whom they were connected. Once contacted, the recipients considered participating in the water conservation campaign. The purpose of testing two different group sizes (targeted, non-targeted) was to estimate how quickly the measures are likely to be adopted by the two population sizes and determine the trade-offs associated with targeting smaller groups.
The leaflet campaign is a traditional communication strategy that entails adding promotional material to the customer's water bill which is meant to inform them of the conservation campaign. The strategy was selected because it is a good way to target individual households and is a strategy that is often applied in Canadian municipalities (Waller et al., 2007). Furthermore, research undertaken by Silva et al. (2010) suggests that mail-in programs are the means by which most residents would prefer to be contacted to receive information about water conservation. In addition to the leaflet campaign, a strategy that makes use of social media was simulated to promote the conservation programs. Social media has become more prevalent over the last number of years and many advertisers are turning to online media to promote their brand. The City of Kingston has a social media presence and communicates to its customers via social media outlets such as Twitter, Facebook, and Youtube (Martin, 2014).
4.5.2 Experimental Design of Communication Scenarios

The communication strategy was modeled using the ABM to test two scenarios. The first scenario was analogous to a fixture rebate program. A single fixture (e.g., a low-flow toilet) rather than multiple fixtures was selected to test the communication strategy for the sake of simplicity and clarity of exposition. The second scenario modeled a water conservation program that would prompt recipients to use less water by modifying their behaviour. In both scenarios, household agents were contacted directly by a conservation agent once a year with a message that prompted them to participate in the program. Results from Silva et al. (2010) were used to inform the decision making of agents in this work. When a rebate was offered (Scenario 1), the agents adopted the fixture with a probability of 0.62 when prompted by the leaflet campaign (Silva et al. 2010). In the second scenario, agents participated in the conservation program with a 0.18 probability when prompted by the conservation agent (Silva et al. 2010). A social media strategy was adopted in addition to the leaflet campaign in both scenarios. The social media campaign consisted of the conservation agent communicating with a randomized subset of household agents directly to simulate communication through social media. The message prompted the recipient household agents to consider participating in the campaign. If the household agents chose to participate when prompted through the social media message, they communicated with two of their social media connections and tried to convince them to do the same. The social media messages were sent every four months from the conservation agent to 6,684 randomized household agents (Martin, 2014). The number of randomized agents who received the social media messages was chosen to match the number of Twitter followers the Utilities Kingston account currently holds. When agents were contacted through social media, the probability that the agent would participate in the program decreased to 0.02 (Silva et al. 2010) for both scenarios. Since previous research completed by Howarth & Butler (2004) demonstrated that mail-in leaflets are often ignored, in this chapter trials were executed for both scenarios where 10%, 20% and 30% of the leaflet recipients took note of and remembered the receipt of the water
conservation leaflet and considered participating in the program. The variable was termed perception level in the results.

4.5.3 Communication Scenarios for Targeted and Non-Targeted Cases
Two cases were examined for both communication scenarios. In the first case, every household agent within Kingston was targeted with the communication strategy. Every household agent in the City of Kingston were sent the promotional material through the leaflet campaign and the Twitter followers where sent the conservation message. The second case consisted of targeting only a subset of 6000 household agents within the wider population with the leaflet campaign. While the social media campaign was identical to the first case, only those 6000 targeted agents could potentially participate in the campaign when prompted.

4.5.4 Energy savings from geographically-targeted neighbourhoods
Subsets of neighbourhoods from the city were delineated into three clusters for the second set of experiments. The clusters refer to a series of homogeneous neighbourhoods within the Kingston city limits which are located in proximity to each-other (Figure 4.5.3). Each cluster had a similar number of households and was located in three distinct regions of the city. The attributes and the distribution of household occupancy for each cluster is indicated in Figure 4.5.4. The Southeast Cluster is an urban area located close to Lake Ontario. The second cluster termed Southwest Cluster consists of four neighbourhoods located in the southwestern part of the city and was comprised mostly of single-family detached homes in a suburban area of the city. The third cluster termed Northern Cluster was comprised mostly of rural neighbourhoods and was located in the northern part of the city. This last grouping of neighbourhoods was farthest away from the water source (L. Ontario) and had on average a higher elevation compared with the other two clusters. The clusters were chosen on the basis of their distance relative to Lake Ontario, their elevation profiles, and on the practicality of implementing a water conservation strategy to target their population.
Figure 4.5.3: City of Kingston water distribution system divided by neighbourhoods. Clusters shown in color and referenced in image.

Figure 4.5.4: Fraction of each neighbourhood clusters (Southeast, Northwest, Northern) and the entire Kingston population that have 1, 2, 3, 4, 5, 6 and over residents per household (household occupancy).
Table 4.5.1 Number of dwellings and elevation of node nearest to the target water conservation population in the City of Kingston.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>No. of Dwellings</th>
<th>Min.</th>
<th>Max.</th>
<th>Avg.</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southeast</td>
<td>6840</td>
<td>76.3</td>
<td>107.6</td>
<td>94.6</td>
<td>95.6</td>
</tr>
<tr>
<td>Northwest</td>
<td>5995</td>
<td>76.1</td>
<td>113.6</td>
<td>99.5</td>
<td>102.0</td>
</tr>
<tr>
<td>Northern</td>
<td>7550</td>
<td>77.0</td>
<td>124.9</td>
<td>100.3</td>
<td>101.9</td>
</tr>
<tr>
<td>Entire Population</td>
<td>52130</td>
<td>75.8</td>
<td>124.9</td>
<td>95.2</td>
<td>95.8</td>
</tr>
</tbody>
</table>

Four scenarios were examined in order to evaluate the effect that the spatial distribution of water savings has on energy use in the Kingston distribution system. Each scenario consisted of retrofitting an equal number of houses with water efficient fixtures (see Table 4.5.2) in different regions of the distribution system, four regions were chosen in total. These campaign objectives are independent from the results of the communication scenarios presented in the previous section and were chosen by estimating the number of low-flow fixtures that would be required to equip the smallest neighbourhood cluster entirely with water efficient fixtures. The number of fixtures was then used as a target to implement in each neighbourhood cluster separately. The existing penetration rates of water efficient fixtures for the base case were estimated at 40% for low-flow toilets and 70% low-flow showers based on values presented in Babooram & Hurst (2011), 70% water efficient washing machines and 90% from water efficient dishwashers based on values from Natural Resources Canada (2013). A summary of the geographically-targeted scenarios is presented in Table 4.5.3. For the baseline scenario, the existing penetration rates presented above where assumed throughout the residential population of Kingston. The “no target” scenario consisted of equipping 3500 houses chosen at random with low-flow toilets, 1700 houses chosen at random with low-flow washing machines and showerheads and an additional 600 houses chosen at random with low-flow dishwashers. The City of Kingston residential indoor water use was calculated using the ABM with the newly retrofitted households. The remaining three
scenarios consisted of retrofitting the same number of households within the specific clusters. The experiments were executed one at a time by modifying the fixture intensity parameters in the ABM. The new water demands for each scenario were evaluated using the EPANET2 hydraulic solver in order to calculate the energy requirements to operate the distribution network pumps.

Table 4.5.2 Campaign objectives for the water and energy reduction scenarios in terms of number of retrofitted homes.

<table>
<thead>
<tr>
<th>Targeted fixtures</th>
<th>Number of retrofitted households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-flow Toilets</td>
<td>3500</td>
</tr>
<tr>
<td>Low-flow Showers</td>
<td>1700</td>
</tr>
<tr>
<td>Low-flow Washing Machines</td>
<td>1700</td>
</tr>
<tr>
<td>Low-flow Dishwashers</td>
<td>600</td>
</tr>
</tbody>
</table>
Table 4.5.3 Summary of scenarios that tested water and energy reductions.

<table>
<thead>
<tr>
<th>Name of Scenario</th>
<th>Description of Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>No homes are retrofitted</td>
</tr>
<tr>
<td>Non-localized</td>
<td>Retrofitted homes randomized throughout city</td>
</tr>
<tr>
<td>Southeast Cluster</td>
<td>All retrofitted homes located in Southeast Cluster</td>
</tr>
<tr>
<td>Northwest Cluster</td>
<td>All retrofitted homes located in Northwest Cluster</td>
</tr>
<tr>
<td>Northern Cluster</td>
<td>All retrofitted homes located in Northern Cluster</td>
</tr>
</tbody>
</table>

4.6 Results

4.6.1 Communication Strategy for Non-Targeted Agents

The first set of experiments consisted of simulating the leaflet and social media communication strategy for both the fixture rebate and conservation campaign and recording the number of simulated years it took to reach participation levels of 1500, 2500 and 3500 household agents when all 52,130 household agents were sent messages. The results for the conservation campaign scenario are presented in Figure 4.6.1. The figure indicates that it took 1 to 2 years for 1500 household agents to participate for all perception levels. Similar timelines were required for the participation levels to reach 2500 household agents under the same conditions. When all the household agents were targeted with the fixture rebate scenario, the participation rate reached 3500 household agents for all levels of perception within the first year (results are not shown).
Figure 4.6.1: Number of years required for the participation rate to reach 1500, 2500 and 3500 household agents when 52,130 household agents were targeted with mail-in and social media for the simulated water conservation campaign. Results are shown for cases where the perception of the mail-in leaflet program is set to 10%, 20% and 30%. Error bars show 95% confidence intervals.

4.6.2 Communication Strategy for a Targeted Neighbourhood of Household Agents

Figure 4.6.2 and 4.6.3 display the number of years it would take to reach three different conservation targets (1500, 2500 and 3500 participant households) based on the leaflet and social media communication strategy. Figure 4.6.2 shows that, when the household agents were contacted to participate in the rebate program, 1500 households participated within 2 to 6 years depending on perception levels generated from the leaflet campaign. The time period increased up to 5 to 15 years when the target was set to 2500 household agents. In order to achieve a campaign target of 3500 participating homes the experiment showed that it took 16 years on average when 30% of the agents were aware of the campaign, 26 years when 20% were aware and an average of 45 years when only 10% were aware. When the conservation agent implemented the conservation campaign where no rebates were offered, shown on Figure 4.6.3, it took on average between 8 and 19 years in order for 1500 household agents to participate in the
campaigns. In order to achieve a participation level reaching 2500 retrofitted households, it took on average 17 years when the perception level was 30%, 24 years for a perception level of 20% and 40 years on average for a 10% perception level. When no rebates were offered, it took over 50 years in order to have a participation rate of 3500 household agents.

![Figure 4.6.2: Number of years required for the participation rate to reach 1500, 2500 and 3500 household agents when 6000 household agents were targeted with mail-in and social media for the simulated water efficiency fixture rebate campaign. Results are shown for cases where the perception of the mail-in leaflet program is set to 10%, 20% and 30%. Error bars show 95% confidence intervals.](image-url)
Figure 4.6.3: Number of years required for the participation rate to reach 1500, 2500 and 3500 household agents when 6000 household agents were targeted with mail-in and social media for the simulated water conservation campaign. Results are shown for cases where the perception of the mail-in leaflet program is set to 10%, 20% and 30%. Error bars show 95% confidence intervals.

4.6.3 Energy Reductions from Targeted Water Savings

The average daily water savings (L/d) achieved by retrofitting 3500 household agents with low-flow toilets, 1700 household agents with low-flow showers, 1700 household agents with low-flow washing machines and 600 household agents with low-flow dishwashers is presented in Figure 4.4.4. The daily water savings are shown for the four separate scenarios where all of the retrofitted households were confined to the respective neighbourhood cluster boundaries shown on Figure 4.5.3 and for a case in which the retrofitted households were randomized throughout the entire city. Figure 4.6.4 shows that retrofitting the household agents in the Northwest Cluster produced the largest level of water savings (on average) while retrofitting the household agents in the Southeast Cluster produced the least amount of water savings relative to the other scenarios. An average of 687,000 L/d of water was saved in the case where the households were randomized.
throughout the City which is slightly less than when the retrofitted households were localized in the Northeast Cluster yet more than the other two scenarios.

Figure 4.6.4: Average daily water savings (L/d) for 3500 households retrofitted with low-flow toilets, 1700 households retrofitted with low-flow showers, 1700 households retrofitted with low-flow washing machines and 600 households retrofitted with low-flow dishwashers.

The average annualized water and energy savings that could be achieved relative to a baseline scenario where no additional low-flow fixtures are adopted are shown in Table 4.6.1. The results were calculated by multiplying the average daily water savings shown in Figure 4.6.4 by 365 days. The table indicates that undertaking the adoption campaign in the Northwest Cluster resulted in the highest level of both water and energy savings. The results suggest that if the campaign objectives presented in Table 4.5.2 were met within that area, 257 ML of water could be saved every year which would lead to annual energy savings of 85,560 kW·h from reduced pumping relative to the baseline scenario of no conservation action. Achieving the equivalent campaign objective in the Northern Cluster would result in 72,234 kW·h annual energy savings while targeting the Southeast Cluster would result in a 62,776 kW·h annual energy reduction.
When the fixture replacements were randomized throughout the city, the potential annual savings were found to be 251 ML of water and 75,431 kW·h of energy meaning that non-targeted water and energy savings were found to be greater than two of the three scenarios where the savings were targeted. The ratio of energy savings to water savings was found to be highest within the Northwest Cluster with a ratio of 333 Kw·h energy savings for every ML of water saved. Again, the second highest ratio was obtained by the non-localized experiment and preceded by both the Northern and Southeastern Cluster.

Table 4.6.1 Average annual water savings and average annual water savings when the campaign objectives were localized within each cluster.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Annual Water Savings (ML)</th>
<th>Average Annual Energy Savings (kW·h)</th>
<th>kW·h savings/ML savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-localized</td>
<td>251</td>
<td>75,431</td>
<td>301</td>
</tr>
<tr>
<td>Southeast Cluster</td>
<td>232</td>
<td>62,776</td>
<td>270</td>
</tr>
<tr>
<td>Northwest Cluster</td>
<td>257</td>
<td>85,640</td>
<td>334</td>
</tr>
<tr>
<td>Northern Cluster</td>
<td>247</td>
<td>72,234</td>
<td>293</td>
</tr>
</tbody>
</table>

4.7 Discussion and Conclusions

The basis for the research presented in this chapter was inspired by considering the complexity that is associated with the design, planning and administering of water saving programs. An effective conservation strategy maximizes water savings, encourages public participation all the while being cost effective. Both social and technical elements such as producing a realistic estimate of achievable water savings, forecasting the public’s willingness to participate and evaluating the potential benefits on infrastructure performance are all facets of conservation planning that are rife with challenges.

The experiments developed in this chapter were intended to demonstrate the use of an agent-based modelling framework that simulates water conservation and efficiency campaigns to tackle
some of these challenges. The framework consisted of representing Kingston households as agent water users and modelling scenarios that were analogous to real-world communication strategies that are used to promote water saving campaigns in communities. Coupling the ABM with a geographic information system (GIS) and subsequently the EPANET2 hydraulic network solver allowed the water reductions to be localized within the Kingston distribution system to test the energy reductions associated with water savings in different areas of the city.

Substantial water reductions were found to be achievable by retrofitting households with more water efficient fixtures. The level of energy reductions was found to vary depending on the location of the water savings. Specifically, retrofitting an equal number of homes was found to produce different levels of both water and energy savings for different neighbourhood clusters. The distribution of household occupancy explains the differences in water savings that were found for the different neighbourhood clusters. Households with fewer occupants tend to use less water which was reflected in the frequency-of-use distributions model parameters. The water reductions that were associated with adopting low-flow fixtures in these households was smaller given the fact that these household used their fixtures (on average) less often. Retrofitting homes in the Southeast Cluster produced the least amount of both water and energy savings. The smaller levels of water savings are explained by the fact that the neighbourhood cluster was located in a more urban area of Kingston where there are more single occupied households.

Retrofitting an equal number of homes in different neighbourhood clusters was also found to generate different levels of energy savings. As expected, the neighbourhood clusters that saved more water also saved more energy however, the Northwest cluster saw the highest energy saved per megalitre of water saved. The results suggest that water reductions achieved in different geographical areas of the distribution system can lead to varying levels of energy savings, at least
in this distribution network. There are a number of factors that could affect the energy requirements of delivering water to specific regions of the distribution system some of which were mentioned in the introduction (topography, distance to source, network configuration). The Northern Cluster of neighbourhoods was located furthest away from the source and had, on average, higher elevation at the delivery points yet the normalized energy savings were smaller than those found in the Northeast Cluster. On the other hand, the Southeast cluster was found to have the lowest levels of energy savings where the users were closest to the source and were at the lowest elevations. Even so, the difference in energy savings between clusters was marginal and given the varying levels of water reductions on any given day, targeting specific neighbourhood clusters in the Kingston distribution system would almost certainly not be worthwhile. This is especially true given the fact that only one case (Northwest Cluster) was found to save more energy than when households were randomly retrofitted throughout the Kingston system.

While the Kingston network is a mid-sized system, applying the same approach to a larger system with more geographically-diverse terrain may produce greater differences in energy savings. Spang & Loge (2015) performed an analysis on a larger distribution system in northern California and mapped the energy intensity of water delivered to specific areas of the distribution system. The authors suggested that more “energy intensive neighbourhoods” could be targeted as a means to achieve greater returns on energy savings. The reality however is that targeting a smaller number of households makes it more difficult to achieve the same level of water savings. The potential trade-off between targeting smaller neighbourhood clusters rather than the entire city was tested for the two communication scenarios. The timelines for the campaign objectives to be met were found to be much shorter when the entire city was targeted compared to when the smaller cluster of neighbourhoods were targeted in both cases. On the assumption that every
household is equally as likely to participate in the program, increasing the number of targeted people will increase the number of total successes. The communication framework incorporated an element of word-of-mouth between agents which mimicked a social media campaign. Information was diffused more quickly through a word-of-mouth framework when roughly half the agent population participated, and the other half was considering participation. When a household agent received promotional material, the message was transmitted to a neighbour to whom it was connected. If however, a household agent was already a participant in the campaign, no message was sent and the chain of communication ended. With an increasing number of household participants, fewer messages were sent between household agents. In other words, as the market approaches saturation, it becomes more difficult to reach the individuals who have not adopted through word-of-mouth. When no rebates were offered, the objective was achieved within a time period that exceeded 50 years. Timelines of this length would be considered inefficient and suggests that a different strategy should be adopted when smaller groups are targeted.

Two types of communication scenarios were simulated, one in which the conservation strategy represented a fixture rebate campaign and the other in which the campaign targeted people’s behaviours. The distinction was made because the campaigns target two different behaviours. Rebate campaigns provide monetary incentives to individuals which allows them to defray a portion of the costs of replacing water fixtures with more efficient ones while conservation campaigns involve asking users to modify their behaviour by using less water. An advantage of replacing fixtures is that households can engage in water savings without having to modify their behaviour whereas behaviours can change over time. No specific fixture was mentioned for the efficiency campaign and no reference was made to specific behaviour for the conservation campaign. The lack of specificity on the campaign scenarios was deliberately chosen given the
limited amount of data at hand. The parameters that governed the likelihood that agents would participate in the programs once contacted were adopted from the Silva et al. (2016) research. Because of a lack of data, it was not possible to make inferences about adoption rates of specific fixtures or behaviours in this research. Although the Silva et al. (2016) research was extensive and surveyed a large sample size, the sampled population did not include Kingston residents. Kingston specific data on user behaviour would strengthen this research. Similarly, the estimation of the existing penetration rates of water efficient fixtures for the Kingston households were based on published Canadian data that was not specific to Kingston. The exact timelines and water reductions presented in this chapter must therefore be interpreted with these limitations in mind. Nonetheless, the general framework presented in this thesis can be easily tailored to situations where more information is available to the modeler.

ABMs have the potential to consider a range of communication strategies in the simulation of water conservation campaigns. The flexible approach makes it ideal to simulate human interactions and to study how these interactions can affect water use and subsequently water distribution network operations. Researchers who examine the social aspects of water conservation have examined the individual motivations that are associated with reducing water use. This research is undertaken with the understanding that an in-depth knowledge of water use behaviour can be useful in designing water conservation campaigns. The advantage of marrying social science research with computational models is the flexibility to run a range of scenarios and include a number of different possibilities, as was demonstrated in this chapter. The difficulty lies in the reality that estimating quantitative parameters based on qualitative research can be challenging. Notwithstanding, scenario-based models are not intended to predict the future (Dziegielewski & Chowdhury, 2012), but rather they are intended to test a range of scenarios and possible futures and provide relevant information for planners. Conservation campaigns often use
a variety of strategies to communicate with the public. This chapter has focused on modelling two specific strategies in order to test how quickly the measures might be implemented, and test whether a geographically-targeted campaign would generate more energy savings than a campaign that was not targeted. The framework demonstrated how communication strategies can affect the outcome of a conservation program and that geographically-targeted conservation programs can affect energy use.

The communication strategy developed for this research was based on strategies that are widely used in municipal government. With the growth in data collection, an opportunity presents itself to monitor the effectiveness of conservation campaigns particularly through the use of social media. Data could be gathered which could then further inform assumptions about social behaviour and lead to stronger modelling assumptions.

4.8 References


Government of Canada.


Chapter 5

Summary and Conclusion

This thesis presented a simulation approach that modeled water conservation campaigns by coupling and agent-based social model with a hydraulic model. The approach was unique as it incorporated modelling the communication strategies that can be used to promote water reduction measures. An illustrative case study was then developed where households, represented as agents, were targeted through a mail-in and social media campaign that prompted them to consider adopting water efficient fixtures. The water demands before and after the campaigns were evaluated through the EPANET2.0 hydraulic network solver in order to calculate the change in energy use stemming from the measures.

The first research question asked what the impact of social ABM diffusion parameters on the rate and speed of adoption of low-flow technologies was. The sensitivity analyses presented in chapter 3 found that the speed and rate of adoption was most sensitive to adoption probability, initial penetration rates and, to a lesser extent, connections per agent. The results can be helpful in the development of future ABMs and to develop an understanding of how the parameters that govern the structure of agent interaction affect diffusion patterns. The connections per agent and link factor are parameters that are difficult to empirically measure. The implication is that, if the adoption rates would have been found to be sensitive to these parameters, the eventual calibration of this network structure would be prohibitive. On the other hand, adoption probability and initial penetration rate can be estimated through household surveys.

The second research question asked what the potential was for various low-flow technologies to reduce water use in the City of Kingston. The results from the sensitivity analyses on water use in
Chapter 3 showed that the increased adoption of low-flow toilets has the greatest potential to reduce indoor water use in the Kingston system, followed by low-flow showers, washing machines and efficient dishwashers. This result can help conservation planners target specific fixtures to maximize water savings.

The third research question asked to what extent water savings produced energy use reduction from the pumping and treatment of clean water in the distribution system. Chapter 3 showed that energy use in the Kingston system is in fact proportional to water use and that a reduction in water use would lower the energy requirements for both pumping and water treatment.

The fourth and final research question was to examine the extent to which geographically-targeted conservation measures could reduce energy use in the Kingston distribution system. This question was explored in Chapter 4 by simulating various scenarios where Kingston residents represented by agents would modify their water use in localized areas of the distribution system. The results showed that retrofitting an equal number of homes in different regions of the distribution system generated different amounts of water and energy savings, however the differences were modest.

5.1.1 Research Contributions

The thesis makes the following research contributions:

1. The development of an ABM to model households water users that can update their behaviour and modify water use.

2. The development of a framework that can be used to simulate water conservation campaigns and estimate energy reductions from reduced pumping and treatment operations.
3. The application of the ABM to develop new knowledge on how social parameters within the ABM structure affect the simulated rate and speed of adoption of low-flow technologies.

4. The application of the ABM to develop new knowledge on the potential water and energy savings in the Kingston distribution system

5. The application of the ABM to develop new knowledge on the effect of the spatial distribution of water use in the Kingston distribution system.

5.2 Future Work

The work presented in this thesis focused on modelling the relationship between water-users and water distribution networks to examine how water savings can affect energy use from pumping and treatment energy in the distribution system. The research showcased how simulation models, particularly agent-based models can be used to capture the relationship between end-users and infrastructure performance. There are some aspects of this research that could be improved in a straightforward way while other aspects would be more challenging to address.

The accuracy of the case study could be improved by increasing the amount of local data. Information that was used to inform the parameters where mostly taken from published studies most of which were not specific to Kingston residents. Local data on water use and existing penetration rates for low-flow fixtures would be useful for calibrating existing water use on a neighborhood level. A model of the Kingston’s water distribution network was provided from the municipality, however pump efficiency curves and leakage data were not included in the model.
Pump efficiencies generally vary as a function of operating head therefore efficiency curves would lead to more realistic results as would leakage data.

The agents in this work made decisions about purchasing water efficient technology when prompted by their peers or a conservation agent. This is a simplification of a complex process of decision making. As discussed in Chapter 3 there are number of factors that have been found to correlate to individuals adopting water efficient fixtures, only a subset of which were addressed in this work. Future work could focus on taking a truly multi-disciplinary approach where multiple stakeholders are engaged in the model development including social scientists, engineers and the public as an example. This approach has the potential to capture the different perspectives of water users and scientists and could lead to more robust assumptions. Surveys, data analytics and interviews could be implemented to better estimate and calibrate parameter values in order to strengthen the agents’ mental models. Finally the model should be re-visited periodically to test the accuracy of the predicted results and inform future versions.