Decision Support Tools for Sustainable Water Distribution Systems

by

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Abstract

Sustainability relies on the balance between economic, social, and environmental objectives. Although seemingly divergent at times, the connections between them elucidate opportunities for improving different components simultaneously. In water distribution systems, aging infrastructure, insufficient funds, water scarcity, leakage, and high energy use have prompted the pursuit of sustainability through different strategies. These conditions demand improvement and create the opportunity to rethink the system. The present study proposes five separate decision support approaches that underlie a systems approach. These address current issues of North American water distribution systems and lessen the gap between research and application.

The first two focus on the interface between users and networks. The relation between user characteristics and demand is studied by building an integrated database to support planning, especially demand management. Data from three Ontario municipalities are used to define metrics, benchmarks, conservation targets, and user clusters. The relation between users and service requirements is further explored qualitatively through a survey on water user expectations, addressing the disconnection between utilities and stakeholders. Applied to the City of Guelph, it informs the utility of knowledge gaps and preferred solutions.
While these approaches concentrate on the needs of the stakeholders, inputs to more thorough planning, the next two assess the resulting systems. A set of energy metrics addresses the issue of inefficient energy use and provides indicators of system capacity, costs, and greenhouse gas emissions. The metrics are applied to the Toronto water network, and allow for the identification of specific areas for improvement. In order to further evaluate how complex networks respond to variations, a more comprehensive set of performance metrics are proposed and applied to two example networks.

The final approach seeks to improve the design process by reducing the computational intensity of optimization procedures and thereby allowing for the analysis of more system objectives and uncertainties. The procedure, applied to Anytown, uses shorter time cycles to approximate full costs of systems with varying loads. Overall, the approaches facilitate current-day decision-making by applying systems thinking to the development of new solutions that collect, integrate, analyse, and re-interpret readily available data and models.
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The thesis not only contains three studies that were applied to Ontario water utilities but was largely shaped by these interactions, which elucidated the needs of current local water systems and the gaps between research and practice. Two of these projects were made possible through the Showcasing Water Innovation program funded by the Ontario Ministry of the Environment. As part of these projects, I had the privilege to work with Kathryn Grond from the University of Toronto’s Cities Centre, as well as Katelyn Margerm and Tom Weatherburn from the Canadian Urban Institute, and to be supervised by Jeff Evenson. These people guided me through the
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1 Introduction

1.1 Re-envisioning our Water Systems

Historically, water infrastructure was widely developed and installed throughout the 20th century. As a result of both this long history and a certain complacency that developed with the newly constructed systems, many systems face the current challenge of managing aging mains, appurtenances, and equipment, more subject to leakage, failure, and in need of costly replacement. Certainly experience has been gained, technologies have advanced, and in the era of information, with better and less expensive sensors, computing, and communication, more data can now be collected and processed than ever before. Given this convenience, the task of nearly replacing entire systems can be seen as an opportunity to right the wrongs, to adjust design to the new paradigm of sustainability. Much of the data collected, however, is not used to its full potential, an issue addressed in chapter 3.

Designing, operating, and maintaining water supply systems is generally perceived as an engineering problem. The goal is to deliver clean water to users according to standards that ensure safe and adequate service. Within the ranges allowed by these standards, design and operation is then adjusted to meet consumer requirements and theoretically minimize (or at least constrain) costs. This obviously depends on the definition of costs, the possible inclusion of various externalities, and the time span considered in decision making. These issues are further explored in chapters 6 and 7, in which a performance index, and a cost-based optimization technique are proposed, respectively. If the quality of the service produced by the system depends so much on what has been defined as safe, reliable, and satisfactory, then one question begs to be answered. Have we defined performance appropriately, that is, are the objectives and constraints of this “problem” correctly stated?

Nevertheless, it is only fair to admit that even this query is instilled with an engineering bias. From a physical perspective, the problem to be solved by water distribution is to move a liquid with given properties from a source to the various locations of demand. In order to do so, a set of
pipes and appurtenances is designed and built. As the liquid passes through these components not only may there be leaks, but mechanical energy is irreversibly converted to thermal energy, becoming both less valuable and less available for other uses. From a strictly physical standpoint, an efficient system should tightly limit the amount of water lost, energy wasted, and materials used.

A water supply system, however, is more than a collection of engineered pieces – it is intended to supply a need that is highly human. And because humans are complex, water demands are hard to predict, particularly considering they fluctuate moment by moment, as well as hourly, seasonally, yearly. Historical data can be used to predict future demands as well as support conservation strategies, an application explored in chapter 3. Demand greatly depends on customer behaviour as well as their response to pricing, technological and conservation initiatives. Water supply systems physically connect the natural source of water to the consumers, which may be residential, commercial, industrial, or agricultural, located, perhaps in a seemingly haphazard manner. The gamut of services delivered includes hydration, sanitation, cooling, increasing human comfort, aesthetic enhancement, facilitating or limiting the rate of chemical reactions, and firefighting. These, among other regional, cultural, and climatological differences lead consumers to use and perceive water differently. Feedback from the users, as sought in chapter 4, can help utilities understand these distinctions as well as identify system issues.

The availability of water can also vary. Changes in the balance of the water cycle due to global warming might increase or decrease local water availability and will almost certainly alter demand. The mitigation of these impacts would require the reduction of greenhouse gas emissions. Adaptation might also include the alteration of operations and infrastructure. In chapter 5, greenhouse gas emissions due to energy use are calculated and their variation according to demands and time of day are discussed.

Still, from another perspective, economic, the goal of the utility is to deliver water to the consumer while producing controlled or perhaps even minimum expenditures and receiving
sufficient revenue to cover capital and operational costs, as well as externalities. Water system decision-making is multi-objective; it is bound by policies, and legislation, yet engulfed in environmental, social, and economic considerations and goals. The balance of these three, it is argued here, is the goal of sustainability, hence they cannot be analysed separately nor their interactions discarded. However, an excessive number of factors can hinder the planning process. Models, for instance, become too complex and computationally intensive. A map that is too detailed can confuse and distract as much as direct and inform.

The proposed decision support tools, which can be applied separately, seek to address distinct issues currently faced by water distribution systems by identifying and leveraging connections between the environmental, social, and economic spheres. A review of issues faced by North American water distribution systems, especially in Ontario, Canada, revealed the following as most predominant: water scarcity, leakage, aging infrastructure, and the so called infrastructure funding gap. These have repercussions in all spheres. Accordingly, the best solutions not only address these three areas, but might also solve multiple issues simultaneously.

The decisions supported by these tools, presented hereafter in more detail, are related to sustainable planning, such as water distribution network infrastructure design, operation, and maintenance, demand management, and stakeholder engagement. The first two approaches address the interface between users and the water distribution network. While the first studies the quantitative relation between user characteristics (land use and demographics) and demand, the second qualitatively assesses user behaviour and expectations, as well as their correlation to utility concerns and strategies. These tools, thus, focus on how users perceive, influence, and are affected by the water system. They collect and organize readily available data, generating important inputs for improving design by better aligning the system with stakeholder requirements.

The next two approaches concentrate on the infrastructure, particularly with regards to the influence of design, operation, and maintenance strategies. Metrics are proposed to evaluate the energy efficiency and long-term performance of networks. Lastly, given the demands of the
consumers, the performance requirements of the infrastructure, and the financial needs of the utility, the final approach seeks to improve design. Overall, the tools address current issues from a systems perspective by analysing system interconnections and applying readily available resources.

Users of the tools are expected to be utility managers and engineers, as well as consultants. Indeed, three of the five proposed tools, those expounded in chapters 3, 4, and 5, have been applied to Ontario water systems. Nonetheless, they can be applied to other systems. The tools are intended to be simple so that data and hydraulic models currently available at most North American utilities are sufficient to initiate the analysis and identify issues. Additional data requirements and modelling will depend on the utility’s issues, time and cost constraints, as well as the current level of data collection, modelling, and sustainability planning.

1.2 Thesis Objectives

The primary objective of the thesis is to develop stand-alone decision support tools tailored to the main issues as well as the technical and data capacities of current water distribution systems. Specific objectives are described below.

1. The sustainability of water distribution systems depends on the balance of environmental, social, and economic objectives. These, however, are not independent. A complex network of connections and feedback loops between stakeholders, infrastructure properties, local conditions, costs, and environmental impacts exists within water systems. Many previous studies, however, have not acknowledged these connections and focus on independent objectives, failing to assess system wide repercussions of potential decisions. In chapter 2 these connections are described in a conceptual map of water systems. This seeks to facilitate a systems approach to decision-making and identify modifications that can leverage positive feedback loops.

2. Network design, local conditions, pricing, and user characteristics influence water consumption. Demand management can use these connections to understand drivers of
consumption, benchmark water use, and define conservation strategies. Although most
Canadian water utilities have access to billing records, demographic census information,
and structural data from property tax assessments, this information is not used to its full
potential. Previous studies have established that user demographic and dwelling
characteristics impact water use and can be used to forecast it. Chapter 3 extends this
notion by building an integrated database of this data from three Ontario municipalities,
with the objective of defining benchmarks and targets for water conservation, as well as
water user segments.

3. While chapter 3 explores the quantitative connections between user characteristics and
their water demand, chapter 4 investigates the various connections between user
perception and system properties, such as water availability, pricing, infrastructure
performance, planning, and communication. Because users automatically monitor system
conditions continuously, customer feedback, although often overlooked, has been shown
to be an important resource for water utilities. Previous studies, however, have focused
on specific issues or user willingness to effect change. While the City of Guelph has
already conducted surveys about water user opinion on programs and by-laws, the survey
presented in chapter 4 sought to assess system-wide expectations in order to gauge and
improve the correlation between user and utility concerns. Results inform the City’s
current Water Supply Master Plan Update. Furthermore, a business model perspective,
not generally applied to water utilities, is taken in chapter 4 to analyse current Canadian
water utilities, particularly Guelph Water Services, with the objective of discussing
improvements through a new lens that can be more intelligible to utility managers and
policy makers.

4. With regards to infrastructure, the water energy nexus has been shown to be an important
connection. Energy consumption is responsible for the majority of costs and greenhouse
gas emissions of water distribution. Furthermore, energy integrates the two principal
hydraulic products of the system: water flow and pressure. Accordingly, previous studies
have applied power or energy metrics to assess the efficiency and performance of
distribution networks, but only at an aggregated system level. Chapter 5 seeks to define energy metrics at a component level that can be used to identify specific pressure districts, mains, pumps, or tanks where changes are most beneficial, as well as to compare the energy efficiency of water distribution networks. The proposed methodology is applied to a case study of the City of Toronto water distribution network.

5. Chapter 6 extends this analysis of network energy efficiency in order to assess system performance under varying conditions. Previous studies of water distribution system performance have failed to represent network connectivity with varying loads and multiple network components, network capacity to deliver demand under uncertainty, and ability to recover after emergencies. Chapter 6 seeks to define a performance index that addresses these limitations and that can be applied in establishing rules of thumb for increasing system performance. The proposed performance metrics were applied to two example networks and variations of these in order to assess, at least in a provisional way, their relevance, sensitivity to changes, and compare results to existing metrics.

6. Given the various connections explored in the abovementioned chapters and the multiple objectives of water distribution systems, chapter 7 proposes a non-computationally intensive design optimization approach that can be used to support the assessment of various system alternatives. Recent studies have focused on developing complex optimization techniques for simple hypothetical networks. These techniques, however, are seldom applied to real systems, perpetuating a gap between research and practice. Accordingly, chapter 7 seeks to define a simple technique that can be used to select pipe sizes that minimize capital, operational, and damage costs of networks with varying loads.

1.3 Overview and Layout

The structure of the thesis is shaped by the writing and preparation of conference and journal papers. In particular, chapters 3 to 7, each related to one of the proposed tools, are based on manuscripts accepted by or submitted to either the Water Resources Management Journal or the
Journal of Water Resources Planning and Management. Nevertheless, the connections between these are described throughout the thesis.

To contextualize and set the tone of this work, chapter 2 provides a brief literature review of sustainability and how it pertains to water distribution systems. It outlines the definition of sustainability and the approach towards achieving it that is applied in the following chapters. Given the need to balance multiple interconnected objectives in order to increase system sustainability, the connections between stakeholders, local conditions, and infrastructure are described in a conceptual map of the system. This facilitates the visualization of feedback loops and the effects of altering one component of the system. Literature related to specific themes, pertinent to different decision support tools, are reviewed separately in each chapter. There might nonetheless be overlap between chapters.

The following chapters propose separate approaches for improving the sustainability of water distribution systems. The tools address current major issues of these systems by collecting, integrating, analysing, and re-interpreting readily available data and models, facilitating their application by utilities and consultants today. Chapter 3 is based on the manuscript entitled “Building an Integrated Water-Land Use Database for Defining Benchmarks, Conservation Targets, and User Clusters”, published in the Journal of Water Resources Planning and Management, reproduced herein with permission from ASCE. In it, water billing records, land-use and demographic data are integrated to better understand and quantify demand in different sectors. This not only organizes information and makes inherent correlations easier to understand, but reduces “silo mentality” and facilitates communication to policy makers. Data was integrated for three Ontario (Canada) municipalities, Barrie, Guelph, and London. Based on this information, water use metrics, benchmarks, and targets for conservation were defined. Furthermore, water user clusters were identified through self-organizing maps, K-means, and hierarchical clustering, and selected according to their pseudo-F and Rand statistics. A summary tool was created with these results facilitating visualization as well as the communication with consumers and policy makers.
Chapter 4 is based on the manuscript entitled “Collectively Re-envisioning the Water Utility Business Model”, submitted to *Water Resources Management*. It furthers the analysis of the demand side through qualitative research. From a business model perspective, water system issues and how they relate to business components, such as pricing, stakeholder integration, and value creation, are discussed. Stakeholder feedback is found to be an instrumental tool in revising a business model. Accordingly, a survey was developed and conducted with residential water users in the City of Guelph, ON, Canada. Questions span across user awareness, preferences, concerns, motivations, and priorities in order to improve the business on different fronts: infrastructure, conservation programs, communication with users, and long-term strategies.

In chapters 5 through 7, the focus shifts to infrastructure performance, its assessment and improvement. Chapter 5 is based on the manuscript entitled “Energy Metrics for Water Distribution System Assessment: A Case Study of the Toronto Network”, submitted to the *Journal of Water Resources Planning and Management*. Energy metrics are proposed as indicators of system capacity, efficiency, GHG emissions, and costs. The five metrics, energy supplied, dissipated, lost, potential, and delivered are calculated by network component. They integrate the two key water distribution system parameters, pressure and flow and can, thus, be easily obtained from standard EPANET hydraulic modeling outputs. The metrics are applied to a case study of the City of Toronto water distribution network, two operational scenarios of which were modeled in EPANET. Mapped results provide a geographical snapshot of the system, and allow for better identification of pressure districts, or even specific mains, pumps, and tanks, where dissipation is high or energy delivered is in excess, and changes are most beneficial.

Chapter 6 is based on the manuscript entitled “Performance Index for Water Distribution Networks Under Multiple Loading Conditions”, submitted to the *Journal of Water Resources Planning and Management*. This chapter proposes a performance index that can used to assess systems with varying loads. The index is the geometric average of four performance metrics: reliability, vulnerability, resilience, and connectivity. These are based on the energy efficiency defined in chapter 5 and the structural ability of the system to deliver water under different
conditions. In order to assess the proposed metrics, these were applied to two example networks and variations of these with different redundancy increasing strategies. Network configurations with loops, fewer loops, increased diameters, and different levels of storage and pumping were modeled. Furthermore, for each of these, three 1-day scenarios were analyzed: normal demand pattern, fire flow during maximum demand, and pipe break during peak demand. Results are compared to existing metrics and used in establishing rules of thumb for increasing network performance.

Chapter 7 is based on the manuscript entitled “Cost Gradient Search Optimization Technique for Water Distribution Networks with Varying Loads”, submitted to the Journal of Water Resources Planning and Management. In it, a cost gradient based pipe sizing optimization technique is proposed. In order to account for risks and add redundancy to the network, the gradient includes damage costs, as well capital and operational expenses. Constraints on extended period analyses are relaxed and shorter time periods are used to approximate total costs, significantly decreasing the computational intensity of the method. This should allow for the comparison of more storage, pumping, and control alternatives, which have typically relied on engineering judgement and experience. The technique was applied to the Anytown example network, which is well documented in the literature, has a realistic topological complexity, and varying demands. Results are compared to previous studies as well as amongst network scenarios.

Finally, chapter 8, the last chapter of the thesis, summarizes the contributions of the present research, and discusses potential further implementation of the proposed decision support tools, as well as possible extensions to the thesis.

1.4 Publications Related to Thesis Research

As previously mentioned, the contributions of this research have been disseminated in published format. The published works are listed below in chronological order


As primary author, I wrote the papers listed above, and performed the research as well as analysis presented in them. The co-authors are either my PhD thesis supervisor, Prof. Bryan Karney, or supervisors of the research conducted with Ontario municipalities, together with the Canadian Urban Institute. The co-authors provided ideas and insights, proofread and edited the
manuscripts before submission. I have received permission and endorsement from them to include in this document all materials listed above.
2 Sustainability of Water Distribution Systems

2.1 Definitions of Sustainability

The first step in developing tools for improving system sustainability is establishing a clear definition of the goal, so as to direct analysis. The pioneering definition of sustainable development, “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development - WCED, 1987), is commonly cited as a preliminary remark. A broad concept, however, creates a wide spectrum of possible interpretations. It is repeated by Fischer and Amekudzi (2011), and Solis et al. (2011), yet only to be elaborated upon, and altered to meet specific needs. The former stresses the role of infrastructure in maintaining appropriate levels of quality of life, whereas the latter establishes a sustainability index based on measures of reliability, resilience, and vulnerability.

According to WCED (1987) as well, limitations to the environment’s ability to promote inter-generational and intra-generational equity are imposed by the state of technology and social organizations. The three pillars of sustainability are, thus, environment, society, and economy. However, the reason for a failure in forming a collective vision of sustainability might lie in the segregation of subjects, which are inherently related (McMichael et al., 2003). Liner and deMonsabert (2011) apply a triple bottom line goal programming model in evaluating alternatives for water supply. However, connections between the goals are neglected, and economic trade-offs, which exclude externalities, are the key indicators used in the assessment.

Although most authors recognize the three principal components of sustainability are economy, society, and environment, the degree to which these are related and interconnected is not agreed upon. For instance, Kleine and von Hauff (2009) depict this triple bottom line in a ternary plot, where each vertex represents 100% focus on one component. Therefore, there cannot be 100% focus on all elements simultaneously. This frames sustainability as a tension or a tug-of-war, a conflict between trade-offs. Placet et al. (2005) also propose a triangular representation of
sustainability. The focus, however, is not on trade-offs, but on interactions between the cornerstones of sustainable development. The integration of the three goals, supporting each other, should enable successful sustainability-focused strategies.

Herein, sustainability is defined as a goal, to better balance the multiple economic, environmental, and social objectives of a system. The goal is not simply to maximize total performance under the selected criteria, which could cause an undue focus on one of the objectives, but to consistently increase the fulfillment of all objectives. This is related to the concept of non-inferior solutions. It is not, however, a fixed goal. Sustainability is understood as a continuous process of improving the balance between system objectives by leveraging connections and feedback between components.

The best approaches for improving this balance, thus, depend on the system, its main issues, interconnections, as well as available information and tools. These affect the potential benefits and costs of modifying the system. While the previous chapter discussed current issues of water distribution systems, the following section, 2.2, examines available tools for assessing sustainability, and section 2.3 describes the connections within these systems. Because sustainability entails a continuous improvement process and most systems are complex, this will generally involve several distinct strategies. In order for these not to become piecemeal approaches and cause unforeseen negative impacts, they must be envisioned as part of an interconnected long-term system plan.

### 2.2 Water Distribution System Assessment

Although indicators of water system performance have already been recommended, (e.g. American Water Works Association (1995) and Alegre et al. (2006)) the examples of applications given by the authors mostly include the evaluation of past operations and identification of trends, and seldom the assessment of future alternatives The establishment of long-term goals and development of corrective actions is suggested, but how to optimally do so
Alegre et al. (2006) list various performance indicators, which are separated into six classes: water resources, personnel, physical, operational, quality of service, and economic. Most measures are expressed as percentages or divided by total water supplied for better comparison. Utilities are expected to measure and manage the indicators that most pertain to their issues and mandate. However, selecting the best indicators is found to be a complex process for some utilities.

The American Water Works Association (1995) establishes three performance criteria for water distribution systems: adequacy, dependability, and efficiency. Adequacy concerns the delivery of acceptable quantity and quality of water at sufficient pressure. Measures for this criterion are pressure, flow, water quality, customer complaints, responsiveness to customer complaints, and customer satisfaction. Dependability indicates the level of consistency in providing water that meets requirements. Service interruptions, water quality violations, inoperable valves and hydrants, and main breaks are measures for this criterion. Efficiency reflects how well resources are used in the system, specifically energy and water, related to unaccounted-for water and pumping efficiency, respectively. There are, thus, three types of measures: hydraulic, water quality, and customer perception.

Sahely et al. (2005) also provide a set of sustainability indicators. Four types of criteria for urban infrastructure systems are established: social, economic, environmental, and engineering. Under generic sub-criteria, (e.g., resource use) indicators (e.g., electricity use, water use, and chemical use) differ according to the type of infrastructure. From a list of indicators for urban water systems, those applicable to water distribution are:

- Environmental: electricity use, water use, water quality (BOD, N, P);
- Economic: operations and maintenance costs, extent of reserve funds, research and development investments, user fees;
- Engineering: service interruptions, water losses-leakage;
• Social: connections to water and sanitation service, incidence of waterborne diseases.

However, only a portion are applied by Sahely et al. (2005) and Sahely and Kennedy (2007), as they are not meant to be exhaustive assessments.

A more decision-attuned approach is proposed by the Institute for Sustainable Infrastructure and Zofnass (2012). Their rating system categorizes a project’s contribution to sustainability into two key areas: efficiency of the project and alignment with social needs. However, the framework is not limited to water systems and the performance is scored by points, notably prone to subjectivity. Invariably, water distribution decisions involve the harmonizing of multiple goals: economic, social, environmental, and everything in between. Ergo, a multi-objective analysis is required. The target of such an analysis may be to find a set of alternatives which forms the best possible trade-off surface, the Pareto optimal front (Farmani et al., 2005). The task of choosing a solution remains with the decision maker, and is, thus, subject to individual preferences.

Another option is to simplify the analysis by amalgamating the objectives. However, in order to do so, weights must be assigned to the different objectives, a process which is also not straightforward (Montalvo et al., 2010). Biases, values, and cultural paradigms are always present in decisions, from selecting a methodology to defining a solution. The first step in reducing subjectivity is to recognize it and become aware of the value systems of stakeholders (Stefanovic and Stefanovic, 2005).

The mapping of system interactions can contribute to the understanding of the role of specific components in water distribution and how seemingly disparate objectives are connected. Rehan et al. (2011) and Rehan et al. (2013) applied a system dynamics approach in the analysis of financially sustainable water and wastewater policies. Feedback loops were outlined and used in the simulation of alternatives. For instance, the choice of infrastructure not only dictates impacts in the construction phase, but also affects operations. The poor condition of pipes increases energy dissipation, leaks, pressure requirements, and costs.
The exploration of correlations, determining factors, and sensitivity of the system, made possible through the dynamics approach, can also assist in the identification of strategies which will produce the most positive connections. Sustainability ceases to be a cumbersome task of harmonizing incongruous goals, to become the search of balance between intertwined objectives.

Life cycle analyses (LCAs) provide further insight into the importance of each component and phase of a system’s life cycle. Studies of water systems (Stokes and Horvath, 2011) have indicated that the operational phase is responsible for great part of environmental impacts, 67% of greenhouse gas (GHG) emissions, significantly due to energy use, which contributes to 50% of total GHG emissions. Similarly, according to the Electric Power Research Institute (2002), approximately 80% of municipal water processing and distribution costs are for electricity. Regardless of size, the principal use of this electricity is for pumping treated water to the distribution system, which represents about 80 to 85% of the total electricity consumption for surface water systems. Groundwater systems generally require 30% more electricity.

In accordance with these findings, Racoviceanu et al. (2007) narrowed the scope of a life cycle inventory of a water treatment facility to only include energy consumption and GHG emissions of the use phase. It is important to note, however, that maintenance and replacement costs of aging infrastructure are also an important expenditure of water utilities during operation. Although components of the system reach the end of their life-cycle, they are constantly being repaired or replaced in order to provide a continuous supply of water. Toronto Water (2005) estimated 43% of yearly water and wastewater expenditures are capital, related to the improvement of the system. Furthermore, 71% of these are used in the upgrade, rehabilitation, and replacement of plants, sewers, and water mains.

Because pipe assets have long life spans, most water systems that were built in the 20th century are only now facing the need for extensive pipe replacement (American Water Works Association, 2012). Aging water mains are subject to more frequent breaks, which threaten public health and safety, and may cause significant damage and inconvenience to the communities. Albeit the high costs of reinvestment, delaying replacements is generally worse in
the long term. In order to analyse the effect of infrastructure and operational changes on the life cycle of a system, models are usually applied with the intention of reducing generalizations and producing detailed estimates. Filion et al. (2008) evaluated different pipe replacement scenarios by employing the EPANET2 hydraulic model (Rossman, 2000) in conjunction with a pipe-aging model. A replacement period of approximately 50 years was found to yield the minimum energy expenditure. EPANET2 was also applied by Ghimire and Barkdoll (2010) in their analysis of altering water distribution system properties. Decreasing water demand, main pump horsepower, and booster horsepower, produced the largest energy savings.

Modelling, however, does not diminish the importance of data collection. Both approaches are explored in the following chapters. Time series of different parameters of the system can assist in calibrating the hydraulic model, establishing indicators of sustainability, as well as providing a window into broader system dynamics. Aly and Wanakule (2004) and Cutore (2008) predicted short-term water use based only on past demand and weather conditions. Nonetheless, additional data on the consumers might uncover other significant correlations.

Stefanovic (2000) cautions against solely applying indicators for assessing system sustainability. These can narrow the scope of the evaluation, and oversimplify a complex process, particularly if they fail to account for connections. Oftentimes the implicit judgements and worldviews that underlie the identification and prioritization of indicators are not articulated. Qualitative research can supplement assessments and determine if specific strategies realistically acknowledge and respond to influences of stakeholder paradigms, expectations, and values.

Sustainability analyses can, thus, draw on previous LCA studies as means to define the scope of assessments and alternative strategies, as well as establish key parameters for comparison. Data on the infrastructure, its setting, and its stakeholders supplies more specific information that can be used to confirm or revoke the previous assumptions as well as define more detailed priorities. Then, modifications to the water distribution system can be simulated in a model, and evaluated according to quantitative and qualitative indicators.
2.3 Conceptual Map of the System

Previous studies have analysed the causal loops of water systems and, due to their complexity, focused on different aspects of these. Giacomini et al. (2013) studied the urban water cycle at a watershed level and identified three main feedback loops, shown in Figure 2.1. The first loop describes the stabilizing effect of water conservation, which increases as water availability decreases, and reduces water use. The second loop depicts the balance between population growth and land use restrictions as it affects water use. The third loop represents the influence of land use on runoff, infiltration, groundwater recharge, and, thus, on water availability. Because the study was concerned with the system at a watershed level it does not depict the influence of network properties. Nevertheless, it also neglects the impact of stakeholder behaviour on system decision making.

Rehan et al. (2011) focused on the financial feedback loops within water systems, and later, Rehan et al. (2013) also studied the feedback loops involving the physical conditions of the network and its consumers’ behaviour. Each of these is depicted through a separate set of connections, shown in Figures. They represent in detail how each component within these sections is connected and can be applied to quantitatively simulating these interrelationships. Because of the study’s focus on financial management of water network, however, the influence of network design and operation is not explicitly depicted.

Figure 2.1: Causal loop diagrams for an urban water resource system: (a) water use and conservation; (b) land-use/population; (c) land-use/hydrologic cycle (Giacomini et al., 2013).
Figure 2.2: Feedback loops involving finances of water distribution systems (Rehan et al., 2013).

Figure 2.3: Feedback loops involving customer behavior in water distribution systems (Rehan et al., 2013).
Another diagram was proposed by Colombo and Karney (2003) seeking to represent the critical feedback loops in water distribution systems’ operation and performance. Three pillars support the “labyrinth” of water distribution systems, as coined by the authors: demand, capacity, and performance. The focus is, thus, on the ability of the system to meet demand requirements. Although the economic objectives are represented, the influence of stakeholders and system properties is not shown.
Figure 2.5: Causative factors and feedback loops of water distribution systems (Colombo and Karney, 2003).

In order to facilitate the assessment of water distribution system sustainability, the present chapter proposes another conceptual map of water distribution systems that seeks to more comprehensively represent the connections of the system qualitatively. It is not all-inclusive but seeks to illustrate the complexity of the system, particularly with regards to the connections between the financial, social, and environmental spheres of the systems. Relations between these are simplified and summarized in Figure 2.6. Three main types of system elements, which influence the state and characteristics of the system, are distinguished in the map: stakeholders (in capitals), revenue or costs (in italic), system properties (in bold), and other secondary characteristics, which stem from these.
Beginning with the water source (I), the quality of the water withdrawn, which must be treated to meet standards set by a governmental regulatory body, affects the cost of treatment. These costs also depend on the volume of water treated, the sum of user demand and non-revenue water, as well as the location and type of source (surface or ground water), which influence the cost of abstraction and import if that is the case. Furthermore, the availability of water, reduced by local consumption, exports, and natural use to maintain ecosystems, influences stakeholder perception and willingness to conserve.

The design of the water distribution network (II) is based on what is known and what is expected to vary in the given context. The local topography, combined with city planning, determine the elevation differences water will need to overcome, a component in the need for pumping. From a municipal level, urban planning also defines zoning, i.e. the types and density of users throughout the network, and the expected population growth, which together stipulate design demands. Design standards established by the Fire Underwriters Survey in Canada and other regulatory bodies seek to ensure the safety of the systems through the specification of limits for pipe diameters, velocities, as well as pressures and flows during normal and emergency operations.

The time-dependent capacity of this infrastructure to deliver certain flows and pressures under different conditions depends on the design of the network. The relation between capacity, operational choices, and real requirements determines how well the network will operate. The choice of network components (III), their type, material, and dimensions directly affect the hydraulic parameters of the system, and its greenhouse gas emissions. Specifically for above ground elements, such as tanks and pumping stations, the aesthetics and location can also affect user satisfaction.
In addition to how the network is designed, the way in which it is operated and controlled (IV) also affects hydraulic parameters. Operational standards, which are meant to promote safety, define limits for some of these parameters. The occurrence of hazardous events, such as breaks and fires, creates sudden change, which impacts operations. Demands rapidly peak, increasing flow in pipes and dissipation, causing system pressures to drop, sometimes below zero, risking contamination due to the intrusion of surrounding ground water. In order to improve operations, data that is collected and analyzed about the system can be used to increase utility knowledge and feed back into the system.

Figure 2.6: Conceptual map of a water distribution system.

The age and defects of the components of the network, together with the frequency of maintenance, the hydraulic parameters which indicate the stresses experienced by the system, and the local conditions (soil, traffic, and climate) which can further undermine the resistance of
the system, all influence its state of repair (V). The maintenance frequency established by the utility, thus, influences maintenance and repair costs, as well as rehabilitation and replacement costs. The operation of the system generates further costs associated with energy use for pumping, business activities, general and support activities, as well as management and supervision.

The state of repair of the network is related to leakage. Higher pressures increase the amount of water lost, which in turn augments the flow and dissipation in pipes. Therefore, the state of repair affects hydraulic parameters and vice versa. If, in turn, low dissipation and velocities are experienced in the pipes, the time of residence of the water increases, affecting the quality of water within the network. The failure to deliver water according to the flow, pressure, and quality expected by the users can not only result in inquiries and complaints, causing the utility to incur costs, but can even generate more serious social costs in the case of damaging or destructive events.

The amount of water delivered to the users (VI) should meet their reasonable demands. Whether these demands are strictly necessary is another matter, which can be addressed by investments in sustainability programs, specifically for conservation and capacity building. Because water prices are elastic, demands are also affected by pricing. Therefore, if changes are made to the water rate structure, price-induced-use-changes must be considered in estimating the new revenue from user fees. Other sources of revenue, depending on the model adopted by the utility, may include government stimulus funding, tax base, interest, and water exports. The difference between these and total costs determines the balance of funds available to the utility for future investments, be they expected or not.

In general, the paradigms and expectations of the stakeholders (VII), government, Fire Underwriters Survey, utility managers, operators, engineers, water boards, consultants, local users, and other users, affect all aspects of the system. The perceived benefit of sustainability, be it reducing consumption, decreasing leakage, or increasing energy efficiency depends on the combination of infrastructure conditions, quality of services provided, as well as views and
values of stakeholders. This perception dictates what is expected of the system and the willingness to increase its sustainability.

The mapping of these connections, Figure 2.6, facilitates the identification of feedback loops, instances where the modification of one component causes repercussions that affect that same element. This relation is displayed between user fees and total water use, hydraulic parameters and total water use, state of repair and total water use, hydraulic parameters and maintenance frequency, as well as system operations and data available. For each of these pairs, change is effected in both directions. The dynamics which give rise to these loops are more complex and are not described in Figure 2.6 for simplicity.

Another property of the system that can be easily visualized in the conceptual map is the presence of hubs, elements that are highly connected to the rest of the system. The existence of various hubs, can complicate the task of mapping, though, since connections intersect and affect visualization. For instance, the component denominated “all stakeholder paradigms and expectations” is connected to all stakeholders and affected by all other components of the system. Therefore, these relations were not mapped in order to avoid confusion. They are instead meant to be acknowledged as part of that all-inclusive term. Other hubs, which can be identified in the map are network design and hydraulic parameters.

By following the arrows in the map, the cascade effect of altering one component can also be traced. Different from a feedback loop, which is a closed circle of connections, a cascade effect indicates all of the elements affected directly or indirectly by altering one component of the system. Standards, for example, design or operational, affect greenhouse gas emissions, water pressure, water quality, leakage, costs, and revenue. The ability to trace causes and consequences facilitates analysis and can easily inform utilities of indirect connections they might be less aware of. The identification of these features of the system, feedback loops, hubs, and cascades, can be used to its advantage. Because they describe how elements are connected to each other, links can be used to expand positive change over all dimensions of the system.
The map, however, does not describe the degree to which each component influences others. A more detailed, quantitative and qualitative, exploration of these components is required. Whether for reporting requirements (Ministry of Municipal Affairs and Housing Ontario, 2012 and Ontario Municipal CAO’s Benchmarking Initiative, 2011) or internal control (City of Toronto, 2012), many utilities collect data on total water use, water use per capita, total costs, total revenue, infrastructure backlog, leakage, main breaks per km of pipe, and number of household days with boil water advisories. With these indicators, a preliminary assessment of the system can be performed, from which certain issues, opportunities, and obstacles can be anticipated. In order to specify the best solutions, however, more information and analysis is needed.

The complexity of water distribution systems and their multi-objective nature evidence the need for multiple approaches in increasing their sustainability. In order for these approaches, such as pipe rehabilitation, pump rescheduling, rate changes, conservation, etc., not to cause complications due to unforeseen feedbacks, they must consider the connections within the system. The decision support tools proposed in the following chapters investigate and seek to leverage connections within water distribution systems in order to increase their sustainability. The principal connections analyzed or touched upon in each chapter are as follows:

- land use, demographics, and water consumption (chapter 3);
- stakeholder expectations and utility strategies (chapter 4);
- network design, operations, and energy efficiency (chapter 5);
- network design, operations, and infrastructure performance (chapter 6), and;
- network design, water demands, risks, and system costs (chapter 7).

The present chapter has described some of the multiple definitions of sustainability and how they are applied to the assessment of water distribution systems. It is argued that the various connections between objectives of sustainable systems call for integrated approaches that not only acknowledge these relations but also take advantage of them. Accordingly, water system
connections were mapped, facilitating the visualization of feedback loops, hubs, and potential cascade effects.
3 Integrated Database for Demand Management

Amongst the connections explored in chapter 2, are those that influence water demands. User characteristics have been shown in previous studies to be correlated to water use and have been applied in demand forecasting. The present chapter, instead, applies this information to demand management. It integrates water use, land use, and demographic data from three Ontario municipalities and defines key metrics, charts and benchmarks for comparison, targets for conservation, and clusters of users.

Albeit available to many North American utilities, this data is seldom explored by these, particularly in the context of demand management. Nevertheless, the impending water scarcity in certain regions and high costs of system expansions, increasingly motivate water conservation. Accordingly, the municipalities of Barrie, Guelph, and London, ON agreed to participate in the present study and receive actionable information regarding water demand.

This chapter is based on the paper entitled “Building an Integrated Water–Land Use Database for Defining Benchmarks, Conservation Targets, and User Clusters” by Rebecca Dziedzic, Katelyn Margerm, Jeff Evenson, and Bryan Karney published in the Journal of Water Resources Management and Planning and reproduced herein with permission from ASCE. The objective of this chapter is to guide utilities in using data that is already available to better describe their users and target conservation. Doing so, it addresses the issues of water scarcity, high expansion costs, and lack of customer information.

3.1 The Value of Integrating Data

“Divide and conquer”, specialization, is a common motto in solving complex problems, which splits complex realities into a variety of disciplines, sectors, departments, etc. This means, however, that interactions and synergies between the segments are either ignored or downplayed. According to Hussey and Pittock (2012), three major barriers prevent greater integration between
sectors and policy domains: data deficiencies (missing or disorganized), weak existing policies and frameworks (fragmented, inconsistent, lacking review), and cultural inertia/path-dependency (silo mentality). A consistent system for collecting data in an easily retrievable, standardized, and comprehensive fashion is instrumental in managing water demand (Cahill and Lund, 2013). The present study focuses on data as a pathway to resolve the second and third types of barriers. It integrates water, land-use, and demographic data with the objective of facilitating both understanding and demand management.

The United Nations Environmental Programme (2012) reviewed worldwide applications of integrated approaches to water resource management and recognized the need for better information management, stating that “Information is the foundation of good decision-making and planning”, with reference to integrated water resources management in Agenda 21 (United Nations Conference on Environment and Development, 1992). Although progress has been slow (Muste, 2013), this type of effort has been facilitated in recent years due to advances in technology and information exchange, fostering a greater commitment to initiatives in data collection (Maidment, 2008). Bringing together data from different disciplines fills in gaps of information and knowledge (Muste, 2013).

Boyle et al. (2011) stress the fact that utilities already have valuable data at hand. Utility billing data can be used to inform many types of management decisions, such as pricing, conservation marketing, and peak planning. The use of this data is supported by three characteristics: it is available to all utilities; it can be used to target specific customer groups with customized messages that are more cost-effective than broad public outreach programs; and it can enable an understanding of specific customers, leading to localized utility policies and strategies.

Using more detailed data can provide utilities with greater insights on to how water is consumed over space and time (Polebitski and Palmer, 2010). Jorgensen et al. (2009) indicate that demographics, dwelling characteristics, and household composition all directly impact water consumption, conservation intention, trust, perceived behavioural control, perception, and habits. Polebitski and Palmer (2010), as well as Morales et al. (2011) joined utility billing data with
census demographic and property appraisal data to forecast residential and non-residential water use, respectively.

Shandas and Parandvash (2009) suggest that, given current population growth and urban development, approaching water use through the lens of urban planning, namely the structural and demographic drivers of consumption, can improve the effectiveness of water conservation. Brooks (2006) defines water demand management operationally according to five motivators: (1) reducing the quantity or quality of water required for a specific use; (2) adjusting the nature of the task so it can be accomplished with less or lower-quality water; (3) reducing loss in quantity or quality of water in the distribution system; (4) shifting time of use to off-peak periods; and (5) increasing the system’s ability to operate during droughts. Other benefits include deferring and reducing capital works, reducing pumping costs, and increased flexibility of demand-side solutions in adjusting to changing circumstances (Sahely and Kennedy, 2007). Although water demand management can, thus, be multifaceted, the focus here is on conservation.

The Ontario Water Works Association (2006) proposes a method for decreasing demand, which begins with evaluating the system and setting goals. Guidelines include the installation of certain efficiency devices towards the reduction of consumption by a preset percentage. Recommendations for selecting the strategy and target, however, are not given and may be arbitrarily determined by the utility. Morton (2011) suggests establishing a best practice range instead. According to the Morton (2011), there are two objectives in developing a benchmark: (1) determining the appropriate metric to be used, e.g. m³.m⁻².yr⁻¹, L.cap⁻¹.day⁻¹, and (2) determining the benchmark value based on the water consumption intensity across the dataset. The best practice range can be defined as a percentile, such as the first quartile of the dataset. Data mining is, thus, instrumental in establishing benchmarks for different sectors and monitoring improvement.

Dziegielewski and Kiefer (2010) suggest normalizing metrics for comparability. If metrics are being compared for a single utility over time, it should be sufficient to adjust the calculated metrics for weather conditions, temperature and rainfall. Annual changes in the number of users
are accounted for by the scaling variable, such as population or building space. When metrics are compared across different utilities, it is recommended that all external factors that influence water consumption (outside the control of water users) should be considered. However, it is acknowledged that normalization of weather and other confounding factors across different utilities can be problematic. A practical approach is to use metered account-level information for homogeneous groups of customers and the same dimensions of water use (e.g. total annual, seasonal, non-seasonal).

Even though targets may not currently be set across utilities, provincial or national averages provide an important basis for comparison in a larger, yet similar, stage. Environment Canada (2010), from a survey of 530 Canadian municipalities, presents water use rates by province. Average residential flow in Ontario is approximately 267 L.cap^{-1}.day^{-1}, almost 20% lower than the national value of 327 L.cap^{-1}.day^{-1}. Maas (2009) offers a blueprint for a comprehensive water conservation strategy, in which a target of 150 L.cap^{-1}.day^{-1} for Ontario municipalities is suggested. Albeit not at a policy level, this has been accepted by many Ontario utilities as a suitable goal. This target is inspired by the “Target 140” campaign from Queensland, Australia, where water use was reduced from 300 to 140 L.cap^{-1}.day^{-1}. According to preliminary estimates, the goal of 150 L.cap^{-1}.day^{-1} could be achieved passively, simply by installing high efficiency fixtures and appliances in all new homes and point of sale transactions. Therefore, there is clearly potential for further conservation, the feasibility of which will depend on current demands, policies, consumer behaviour, and utility engagement.

Benchmarks for industrial, commercial, and institutional (ICI) water use are harder to find, since there is more variation, especially between different types of industries. Therefore, water use data must be sorted according to property codes or industrial classification codes for better comparisons. Gleick et al. (2003) present water use benchmarks for different industries in California by sector, specifically by Standard Industrial Classification codes. Water consumption is normalized by production or number of employees. South East Water (2006) provides an extensive list of benchmarks per sector based on surveys and literature review. The dates of the references, however, vary between 1997 and 2006, suggesting some of the data may no longer be
current or relevant. The rate of obsolescence will depend on the sector, acceptance of these targets and potential for improvement.

Previous research, as noted above, has stressed the need for conservation planning and underlined the importance of integrated approaches that combine information from different areas to fill in gaps of knowledge. Using practical models, with input variables that can be collected, monitored and used by the utility is key (Donkor et al., 2014). The present study integrates data that is readily available to most Canadian municipalities and their water utilities: water billing records, demographic census information, and structural data from property tax assessments. This information is used to build an integrated database to support decision-making, specifically demand management. Accordingly, benchmarks, conservation targets, and user clusters are defined.

3.2 Methodology

The data mining method, on which this study is based, comprises six steps: problem definition, data preparation, data exploration, modeling, evaluation, and deployment. This process was repeated for three Ontario municipalities, and results were compared. The problem definition frames the succeeding steps by describing study objectives. Data preparation encompasses the process of cleaning and formatting the data, as well as building the integrated database. In data exploration, distributions, trends, and metrics are assessed and compared. The first benchmarks as well as targets for conservation are also established in this phase. Modeling furthers the analysis as user clusters are defined. These results are then evaluated and the model built for data clustering can be applied to different data sets.

3.2.1 Problem Definition

Many water utilities, such as the ones studied herein, bill their customers according to general sectors, i.e. residential, industrial, commercial, and institutional, or even at a flat rate for all users. Although Canadian municipalities have access to land use and demographic data from the
Municipal Property Assessment Corporation (MPAC) and Statistics Canada (Statcan), respectively, most utilities only distinguish users by billing class. This classification is not descriptive, and does not allow for the definition of homogeneous groups of users, which are more suitable for analyzing trends, establishing benchmarks, and targeting conservation. Nonetheless, the more than 100 classes used by MPAC may prove to be excessive for utility needs, especially if different strategies are being used for each different type of consumer. Accordingly, the study seeks to define benchmarks and targets for water conservation, as well as water user segments in three Canadian municipalities, Barrie, Guelph, and London, based on integrated water consumption, land use, and demographics data.

3.2.2 Data Preparation

The integrated databases were created by connecting data from an SQL server, through ODBC (Open Database Connectivity), for easy storage and updating. Database construction was completed as part of a research project funded by the Ontario Ministry of Environment with the Canadian Urban Institute (CUI). Cleaning and formatting of the billing records was subcontracted. This involved joining data from different months, and updating or rectifying inconsistent customer identifier or address formats. Spatial data, relating addresses to roll numbers, parcels, and dissemination blocks was joined by the CUI using their geographic information system (GIS) data. Roll numbers are the property identifiers used by MPAC for tax assessments. Parcels are pieces of land, generally equivalent to properties, and dissemination blocks, equivalent to city blocks, are the smallest geographic areas for which Statcan releases population counts.

The integration of water consumption, land use, and demographic data involved connecting information from four different sources: water utilities, MPAC, Statcan and CUI.

Six tables were generally integrated in the database, with their primary variables listed below, either as categorical (c), or numerical (n):

- Customer Information (utilities): Customer ID (c), Address (c), Rate Class (c);
• Billing Data (utilities): Customer ID (c), Monthly Water Consumption (n);

• Address Table (CUI), created using a series of spatial joins in GIS: Address (c), Roll Number (c), Parcel ID (c), Dissemination Block (DB) ID (c);

• Structural Data (MPAC): Roll Number (c), Year Built (n), Building Footprint (n), Property Code (c);

• Parcel Data (utilities): Parcel ID (c), Parcel Area (n), Building Area (n);

• Demographic Data (Statcan): Dissemination Block ID (c), Population Count (n).

Customer information and billing data are collected for each user, with Customer ID as the unique identifier. Billing data between 2006 and 2011 was collected. These datasets were linked by Customer ID, and then summarized by address so that they could be combined with the address table. After these were joined, water consumption was associated with roll numbers, parcels, and DBs, and can, therefore, be integrated with land use and demographic data. After summarizing by roll number, this data was combined with the structural data. This was then summarized, either by parcel or by DB, to be joined to the parcel or demographic data, respectively.

There are, thus, two primary tables as outputs of this integration process: a parcel table, with water and land use at the parcel level, and a DB table, with water, land use, and population count by DB. This can then be mapped, facilitating the visualization of spatial trends. Guelph, the smallest of the three municipalities had approximately 120,000 inhab. in 2011, distributed in 35,000 parcels. Barrie had 150,000 inhab. and 42,000 parcels (generally equivalent to properties), while London, more populated, had 360,000 inhab. in 99,000 parcels.

Data integration can be a cumbersome process if attention is not paid to differences in formatting, missing values, data inconsistencies, non-unique identifiers, and varying levels of data summarization. That being the case, it is helpful to sketch the integration process beforehand and name queries and tables in a simple, yet descriptive, manner. In addition, after
each query, as data is joined and summarized at different levels, results should be checked, i.e. water consumption, areas, and population. Totals of each parameter should be compared to the initial tables so that a net match percentage can be calculated.

Because the tables contain data at different geographic levels, which can fully contain or overlap each other, as shown in Figure 3.1, the order in which they are joined and summarized is important. Customer ID, address, and roll number, are all point data. However, they are not absolutely equivalent. For instance, a condominium building may be considered as one customer to the water utility, but may have multiple addresses, corresponding to different units. A parcel, roughly a property, is a collection of roll numbers, and a DB, similar to a block, is a cluster of addresses. Even though a parcel is smaller than a DB, it may not be fully contained in one. Accordingly, joins have to be made between tables that are summarized at the same level, in order to avoid duplicating data. Furthermore, special attention should be paid to the identifiers used for the joins, since they should have the same format. Addresses, for example, are generally recorded differently by utilities and MPAC. Inconsistencies in formats also occur between different years of billing data. The final match rate between water use and property codes was 90% or higher for all municipalities.

Figure 3.1: Geographic levels of the different data types and their spatial relations.

Missing roll numbers were substituted with unique dummy identifiers so that land use associated with blank identifiers, when summarized, would not be grouped together. As a result, the data
can remain linked to its address despite the lack of a roll number. Because population counts are only released every four years, and water consumption data is reported monthly, demographic data was interpolated for the years with no census data, and only yearly per capita metrics were calculated. Population was assumed to increase geometrically. Land use data is also not released yearly. In this case, if the year built is more recent than the year of consumption, building footprint and unit (address) count were assumed to be zero. Whenever consumption was null, records were also neglected. Outliers (over three standard deviations away from the mean) were also removed before the modeling phase, represent 2% or less of entries. If unit count, building space, or property area were missing, values were modeled based on similar users with the nearest neighbour algorithm.

Water consumption data is collected every billing cycle, which is either monthly or bi-monthly for the given municipalities. However, different parts of the cities are metered at different times of the month. Therefore, attention must be paid to the difference between reading date and billing date, especially when seasonal use is being calculated. Although two regions may have been billed at the same time that does not mean that the billed water consumption corresponds to the same period for both. The analyzed water data was separated by billing date, although seasonal use was calculated differently based on the billing cycle of the user.

3.2.3 Data Exploration

Because of this study’s emphasis on integrating data, the amount of data and specific interest of the cities in visualizing correlations and targeting conservation, the data exploration focused on bivariate analyses. The primary variables that were analyzed in this phase were monthly water use (m$^3$), unit count, building footprint (m$^2$), year built, property area (ha), population (cap), rate class, and property code. A spreadsheet-based summary tool comparing metrics from all three cities was developed for the communication of results to water utilities, and for use in both result assessment and conveying this information to policy makers, and users. When sharing these results outside the organization, however, care should be taken to avoid disclosing individual information. This implies classifications may have to be grouped, and if data is being mapped, individual properties should not be able to be singled out.
The summary tool graphically represents relations between user characteristics and demand, temporal (monthly, seasonally, and annually) trends of water use, as well as variations within and between water use metrics in property classes and sectors. It, thus, addresses questions regarding the significance of user characteristics to demand management, expectations of future use given changes to these characteristics, and key user types to target for conservation. The tool is most helpful to utility managers and planners, who can easily view and extract summarized information to plan conservation strategies and communicate with stakeholders.

The summary tool comprises three major components: distributions, trends, and metrics. The first two present charts of total water use, whereas the latter has various metrics of normalized water consumption. The distribution of water consumption is presented in pie charts by sector and property code, as well as bar charts of the top water-consuming property codes, the percentage of total water use they represent together with the class coefficient of variation of normalized water consumption. Some examples of figures provided in the tool and the types of conclusions obtained are shown in the results section.

### 3.2.4 Modeling

Given the objective of creating water user segments, the modeling phase applied different clustering techniques in grouping the data. Segments were created within each of the four larger sectors: residential, industrial, commercial, and institutional. Furthermore, for this process to be easily replicable and results compared with other utilities, property codes were clustered through three methods: hierarchical clustering, K-means clustering, and self-organizing maps. According to Vesanto and Alhoniemi (2000), using prototype clusters reduces computational effort and noise since the prototypes are local averages of the data. The same methods were applied without using the property codes as cluster prototypes, and the results compared. Data mining software with a user interface was used to facilitate the visualization and understanding of the process, as well as its modification.

Through a principal component analysis, in which water consumption was set as the target and population count, unit count, building space, and property area as attributes (components), it was
found that all components equally explain the variations in water use. Population count was only included in the analysis of the residential sector, since it is an indicator of residential occupancy, not ICI. The attribute with the highest importance varies between sectors and cities. Correlations between the three parameters for ICI vary, generally resulting above 0.5, and reaching 0.95 in some instances. Because these correlations are not consistent, and occasionally low, no attributes were considered sufficiently similar to be excluded from the modeling phase for ICI. Population count, in the residential analyses, presented higher correlations with the other attributes - at least 0.7, and up to 0.99. Therefore, only unit count, building space, and property area were kept in the residential clustering as well.

The first clustering technique applied, hierarchical agglomerative clustering, minimizes the linkage, dissimilarity within clusters. The algorithm is initiated with the data points as individual clusters, which are progressively merged at each step. This requires defining a type of dissimilarity. Ward’s linkage, which minimizes total within-cluster variance based on weighted square distance between cluster centers, was used. The distance between two clusters is defined as the increment in the sum of squares if these two are merged, as shown in (3.1)

\[
\Delta(A,B) = \sum_{i \in A \cup B} \left( \frac{1}{|A|} \sum_{i \in A} \| x_i - \bar{m}_A \|^2 + \frac{1}{|B|} \sum_{i \in B} \| x_i - \bar{m}_B \|^2 \right)
\]

(3.1)

where \( \bar{m}_j \) is the center of cluster \( j \), and \( n_j \) the number of points in it. At each iteration the pair of clusters with the minimum linkage are merged. This process continues until merging costs jump or the number of cluster becomes too small.

K-means, the second method, assigns a specified number of centroids to the data set and minimizes the total intra-cluster distance (Tan et al., 2006). The number of clusters was optimized according to the silhouette index (3.2), which relates the average distance between a point and all other points within its cluster (3.3), as well as between the point and all points in other clusters (3.4). This approach generally outperforms other internal indices, and its performance is close to that of the best relative indices (Brun et al., 2007).
\[ S(\bar{x}) = \frac{b(\bar{x}) - a(\bar{x})}{\max\{b(\bar{x}), a(\bar{x})\}} \]  \hspace{1cm} (3.2)

\[ a(\bar{x}) = \frac{1}{n_j-1} \sum_{j \in C_j, j \neq i} d(\bar{x}, \bar{y}) \]  \hspace{1cm} (3.3)

\[ b(\bar{x}) = \min_{k=1, \ldots, J \neq j} \left[ \frac{1}{n_k} \sum_{y \in C_k} d(\bar{x}, \bar{y}) \right] \]  \hspace{1cm} (3.4)

where \( S(\bar{x}) \) is the silhouette index, \( a(\bar{x}) \) the average distance between \( \bar{x} \) and all other points in cluster \( C_j \), \( b(\bar{x}) \) the minimum of the average distances between \( x \) and the points in the other clusters, \( d(\bar{x}, \bar{y}) \) the distance between points \( x \) and \( y \). The Euclidean distance (3.5) was applied as the objective function for the K-means clustering, as recommended by Xu and Wunsch (2009).

\[ d(\bar{x}, \bar{y}) = \left( \sum_{i=1}^{l} |x_i - y_i|^{1/2} \right)^2 \]  \hspace{1cm} (3.5)

where \( l \) is the dimension of the data point.

In the third method, self-organizing maps, each node of data is connected to a vector by a specific weight, which defines the cluster. Adjusting the weights (3.6) minimizes the distance between clusters, and the learning rate (3.7) decays at each iteration (Vesanto and Alhoniemi, 2000).
\[ \tilde{w}_{r}^{t+1} = \tilde{w}_{r}^{t} + \Delta \tilde{w}_{r}^{t} = \tilde{w}_{r}^{t} + \gamma_{r}^{t} \left( \bar{x}_{i} - \tilde{w}_{r}^{t} \right) \]  

(3.6)

\[ \gamma_{r}^{t} = \alpha' v_{r}^{t} \]  

(3.7)

where \( \tilde{w}_{r}^{t} \) is the vector of weights for neuron \( r \), \( \gamma_{r}^{t} \) the learning rate, \( \alpha' \) is the value of the global learning rate, and \( v_{r}^{t} \) the neighbourhood kernel. In order to observe the self-organization property, the neighbourhood factor must be a decreasing function of the grid distance between the best matching unit and the neuron being adapted. The best matching unit is defined as the closest neuron to the input.

The Gaussian function was applied for calculating the neighbourhood kernel, as recommended by Lee and Verleysen (2002) to produce better results than the Bubble function. The latter is a discrete function, the kernel is either 1 when the grid distance is less than the neighbourhood radius or 0 if it is greater than the radius. The Gaussian kernel is a decreasing exponential function of the grid distance.

\[ v_{r}^{t} = \exp \left[ -0.5 \left( \frac{d(u,r)}{\lambda^{t}} \right)^{2} \right] \]  

(3.8)

where \( d(u,r) \) is the distance between the best matching unit \( u \) and the neuron \( r \), and \( \lambda^{t} \) is the neighbourhood radius. The size of the map and the radius were selected so as to generate a small number of clusters, similar to what was found with the application of the two other methods.

Hillenmeyer (2005) points out issues for each of the three clustering methods. The hierarchical agglomerative algorithm is sensitive to outliers and might not produce optimal results, if a local, instead of a global minima is found. Additionally, the generated trees might be too complex and hard to interpret. K-means clustering is a faster method. Nonetheless, results are sensitive to the choice of initial seeds. Self-organizing maps can be easier to visualize. However, the solution is sensitive to the starting structure, and there is no guarantee of convergence to representative
clusters. These methods were not only applied to clustering the property codes and their average metrics, but to the parcel data (i.e., water use at property level) as well. In this case, due to the number of data entries, only a sample was used to create the clusters.

### 3.2.5 Evaluation

The results were compared among the three cities, for cross-validation, between the different clustering methodologies, and with or without property codes as the initial clusters. Clusters were validated internally with the pseudo-F statistic, proportional to the ratio between the sum of squares between clusters, and the sum of squares within clusters. For external validation, the Rand statistic was used in comparing the clusters created with parcel level data and property codes. The Rand statistic measures the proportion of pairs of vectors that agree by belonging either to the same cluster and property code or to different clusters and property codes (Brun, 2007). It can vary between 0 and 1, with 1 being the highest score.

### 3.2.6 Deployment

In order to update the clusters with more recent data or model consumption in other municipalities, the data would need to be prepared, links in the database updated or modified, and queries rerun. With this, a new input file for the modeling stage would be created. Since the models will be run in a data mining software, deployment will use the same schemas created for modeling. For the evaluation of the clusters through the pseudo-F and Rand statistics, a program was written.

### 3.3 Results

Residential water use represents more than 60% of total consumption in all three municipalities, combined. The averages of the three cities are presented in Figure 3.2. Overall, approximately 5% of the total water consumption was not assigned a property code in the database, due to formatting issues or outdated property information. Based on a search of the addresses of a sample of users with unassigned property codes, these were found to be from the ICI sectors.
Therefore, ICI water use for the three cities represents more than 32% of total water use, the sum of industrial, commercial, and institutional use shown in Figure 3.2a.

![Pie charts showing water use and users per segment](image)

Figure 3.2: Percentage of water use and users per segment: (a) total water consumption per sector; (b) residential water consumption per property code; (c) residential water users per consumption range in liters per capita per day; (d) commercial water consumption per property code; (e) industrial water consumption per property code; (f) institutional water consumption per property code.

Within the residential sector, single-family dwellings are responsible for consuming around 60% of water. This is the largest water consuming property code across all municipalities. Most residential users in these cities consume more water than the provincial target of 150 L.cap-1.day-1, yet less than the Ontario and Canada averages of 267 and 327 L.cap-1.day-1. Within the commercial sector, shopping centers appear as a top water-consuming property code at around 20% of the total commercial use. Other common large commercial user types are hotels and large office buildings. Within the industrial sector, because the MPAC classification groups a
variety of different industries under one property code, standard industrial properties, only
general information is available. The more informative denominations show the high water
consumption of specific uses, such as distilleries or breweries and water treatment stations. In the
institutional sector, health and educational facilities use the most water. Due to their high
combined water use, these categories of water users are prime targets for water conservation
programs.

Figure 3.3: Yearly and seasonal residential water consumption trends from 2006 to 2011: (a) total use in London; (b)
total use in Barrie; (c) total use in Guelph; and in all three cities (d) use per capita; (e) use per hectare; and (f) use
per unit.
A decrease in residential consumption, from 2006 to 2011, was observed for all three cities, Figure 3.3a, b, and c. Despite the increase in population, gross water use decreased in these cities due to higher water rates as well as an increased focus on conservation, through consumer education, rebates for high efficiency fixtures and appliances, or outdoor water use programs. The rates of decrease in per capita consumption are similar for all three cities. Residents have been reducing their water usage to such a degree, that it counteracts the increase in population. Different trends, however, were observed for low, medium, and high density dwellings. There is also a reduction in water use for more recent building vintages, Figure 3.4. The trends are shown on different scales for each municipality in order to facilitate the visualization of the seasonal components. Values for the city of Barrie were extrapolated from 2009 and 2010 data because of issues in formatting the billing records. Residential water use during the winter remained fairly constant for all cities. The variation in yearly consumption, is thus, greatly explained by higher summer (peak) water use. Note that summer and winter each correspond to three months of consumption and their sum does not equal yearly water use.

Residential consumption per unit, Figure 3.3f, has also decreased, although less intensely than per capita, Figure 3.3d, suggesting there are now more residents per unit in these cities. Trends in water use per building space, not shown, are very similar to those per unit. Consumption per property area has generally decreased as well. For all three cities, residential trends in m³·ha⁻¹, Figure 3.3e, are similar to those simply in m³, Figure 3.3a to c. Therefore, property area does not explain the variation in residential water use over time, but represents water use density. These trends are instrumental in planning, for forecasting future demands, as well as costs and revenue.
Figure 3.4: Residential water consumption per capita by building vintage for Barrie, Guelph, and London.

Figure 3.5 displays two important characteristics of targets for conservation: high water use, indicating a greater significance of the particular user type to the overall system, and potential for markedly decreasing total consumption, given the cumulative effect of various small modifications; and high variation of water use metrics (m$^3$.m$^{-2}$ or m$^3$.unit$^{-1}$) within the class, evidencing the potential for improving practices. Only top water using property codes in Barrie are shown in Figure 3.5 as an example. In all three cities, within the residential sector, target property codes for conservation are single-family households, multi-residential units, condominium units, and row houses. Within the ICI sectors, targets are hospitals, shopping centers, schools, and restaurants. Because industrial property codes are less detailed, and different property types are grouped, it is more difficult to pinpoint targets. By identifying specific property types, communication regarding conservation programs can be tailored to emphasize particular efficiency devices or practices.
Figure 3.5: Percentage of total water use and coefficient of variation of water use metrics for the largest water using property codes in Barrie, ON, Canada.

Given the detailed, parcel or DB level, water consumption data for sectors and property codes, benchmarks can be determined for each. As recommended by Morton (2011), benchmarks were defined as the 25\textsuperscript{th} percentile for each group of users, a convention that accounts for the level of water consumption and user distribution. The frequency of the metrics is calculated according to their denominator, i.e. building space, unit count, property area, or population. For instance, the resulting benchmarks for residential consumption per capita are 172 L.cap\textsuperscript{-1}.day\textsuperscript{-1}, 149 L.cap\textsuperscript{-1}.day\textsuperscript{-1}, and 156 L.cap\textsuperscript{-1}.day\textsuperscript{-1} in London, Barrie, and Guelph, respectively. Naturally, as conservation ensues, benchmarks will change, motivating continuous improvement.

Clustering of parcel level data indicated that users under the same property code tend to group together, i.e., they have similar water use metrics. Therefore, users in the same class, expected to demand water for the same end-uses, yet at different intensities, were shown to consume water similarly at the individual or building area level. However, there is not a clear separation between property codes. Only two to five clusters were formed within each sector, whether the process was initiated with parcel data or property codes. According to the pseudo-F statistic, hierarchical and K-means performed similarly for clustering parcel level data. K-means performed the best in clustering property codes. Based on the Rand statistic, the hierarchical algorithm produces parcel clusters that best match property codes. In the residential sector, hierarchical clustering generated the best clusters as evaluated by the pseudo-F, and those most similar to property codes, according to the Rand statistic. The highest Rand values among all sectors were found for the residential clusters, between 0.94 and 0.96. This, however, is also due to the fact that one property code, single family dwellings, represents more than half of residential users.

Clusters of the parcel data of the ICI sectors correlated less to the property codes, since water use varies more in these classes, and the distribution of the metrics is more scattered. Values varied from 0.4 to 0.7, depending on the sector and the municipality. Although data was clustered at the property level in order to compare to the property code prototype clusters, data was still separated by sector. This distinction, however, was not confirmed by another cluster analysis, in
which sectors were not separated in the input data. Although parcel data from identical property
codes tend to cluster, sectors are not segregated through clustering. Therefore, separating water
users into sectors does not reflect an inherent divide of the data, but facilitates user
understanding.

Because the municipalities are composed not only of different property codes but users that
consume water at different levels, the clusters formed for each city differ. Although clusters
differ, in all three cities, similar property codes tend to cluster, such as different types of multi-
residential buildings, restaurants, shopping centers, hotels, retail stores, and nursing or retirement
homes. Furthermore, within each sector a large cluster was formed, with different property
codes, yet similar water metrics, and a few smaller clusters clusters with similar types of
properties. These smaller clusters, formed in one or more of the three cities, are listed below and
whether their water use metrics are higher (h) or lower (l) than the other users in the “catch-all”
cluster:

- Residential: residential properties with 3 or more self-contained units (h), cooperative
  housing (h), condominium units (l), other residential properties;

- Commercial: restaurants (h), shopping centers (h), hotels and motels (h), banks and
  similar financial institutions (l), retail (l), other commercial properties;

- Industrial: heavy non-automotive manufacturing (h), automotive (h), private generating
  stations (h), water, wastewater, and waste treatment plants (h), distilleries and breweries
  (h), other industrial properties; and

- Institutional: hospitals (h), retirement and nursing homes (h), ambulance and police
  stations (h), museums and art galleries (h), other institutional properties.
3.4 Discussion

The method described herein for integrating water, land use, and demographic data is based on the data available to Canadian water utilities. However, it can be replicated for any utility where this data is collected. For those utilities which do not have access to such information, or which are beginning to plan their database, this study can assist in understanding the usefulness of different types of data, and determining which information should be collected. Altogether the study advocates a departure from the idea of simply collecting the maximum amount of information about the system, to instead collect data that can support measures for system improvement.

Data preparation, as was the case in the present study, can be the most time consuming step of the data mining process, especially when integrating information from different sources. Data was provided at different spatial levels and in different formats. Because this type of research was not the application initially envisioned for the data, steps were not taken by the different data providers towards improving integration. A consensus between different providers would greatly facilitate the process. There should be a realization that data is not confined to sectors, and the exchange of information between departments and organizations is invaluable. Information should, thus, be collected and maintained accordingly. Data should be easily understood by whoever may work with it. Therefore, future databases should evolve to be interoperable.

Based on the difficulties faced in the present work, some recommendations for integrating data are:

- Request a list of identifiers of the data that is to be purchased;

- If subcontracting any part of the process, be clear and specific about the procedure and expected results, since the employed professional might be an expert in data mining, but not water demand management;

- Sketch the structure of the database, input data, joins, queries, and output data, and update as needed;
• Define a descriptive nomenclature for the components of the database;

• Ensure data is formatted consistently throughout;

• Check match rates for each join or query;

• Summarize data to the desired spatial level, before joining; and

• Keep a log of issues encountered.

The applied clustering techniques divided the water users in all sectors into one large group and two to four smaller groups with similar property codes. This distinguishes high or low water using clusters, which is instrumental in selecting targets for conservation. In order to better understand the segments of users, especially those grouped under one large cluster, and create more detailed clusters, further information could be added to the database, such as:

• Unit counts for all multi-unit residential buildings;

• Unknown property codes;

• Standard Industrial Classification codes which are more detailed than property codes;

• Participation in conservation programs;

• Fixture counts;

• Building or plumbing inspections;

• Temporary residents;

• Water metering; and

• User income.
Because the clustering analysis indicated that users under the same property code or similar property codes tend to cluster together, if utilities do not have other, more detailed, information available, these can be used to define segments of water users. This is particularly relevant for improving customer messaging and water rate structures which currently only distinguish between sectors: residential, industrial, commercial, and institutional.

With the results from the data mining process, Barrie, Guelph, and London have information to benchmark their water use internally and externally.

The municipalities have already extended upon this research and used the integrated data as well as the developed tools in targeting larger users for conservation messaging, planning for future water use, reviewing water rate structures, and in aiding communications with consumers, as well as policy makers. Future studies can apply the proposed metrics and integrate more data for other utilities, thus growing a knowledge base for water systems seeking sustainable improvements. This experience can inform policy planners on metrics to be reported by utilities, targets to be set, and reasonable expectations.

### 3.5 Conclusions

The proposed approach can be applied to any utility for which this data available, true for many North American utilities. Because this information is generally not integrated, it can be used to verify previous assumptions as well as support planning in various ways; one of which is demand management. Engineers and utility planners can apply the resulting metrics, benchmarks, and user clusters to inform master planning, set conservation goals, and improve communications regarding conservation. The metrics allow for the comparison of normalized water consumption and promote further investigation into the causes of higher water use of certain customers within a given sector or property code. The clustering analysis indicated that water users, especially residential, within the same or similar property codes tend to cluster together. Therefore,
property codes represent different customer types and can be used not only to compare metrics, but also in segmenting water users if more data is not available.
4 Collectively Re-envisioning the Water Utility Business Model

Chapter 3 outlined a methodology for integrating data that is already available to many utilities and transforming it into actionable information. It applies customer data, i.e. water use, land use, and demographics to defining benchmarks, targets for conservation, and customer segments. Thus, a quantitative view of conservation is taken, whereas the present chapter qualitatively explores user characteristics, utility approaches, and how they relate to the system. Therefore, the connections between stakeholder expectations, infrastructure performance, and utility strategies, briefly described in Chapter 2 are herein explored.

The provision of water is a unique service. Consumers use it in various different ways, and no one receives the exact same product. Many of the issues in water systems are caused by the failure to resolve these complexities. Previous studies have shown that customer feedback can be instrumental in managing water systems. While surveys have been conducted in various cities, including the City of Guelph, regarding specific water issues or utility plans, the proposed survey assesses system-wide expectations in order to gauge and improve the correlation between user and utility concerns. The survey was conducted with Guelph water users with the objective of assessing their awareness, concerns, motivations, and priorities in order to improve the system on different fronts: infrastructure, conservation programs, communication with users, and long term strategies. Furthermore, results are discussed from a new perspective (at least for water utilities), that of a business model. This perspective motivates an analysis of the system in order to improve management. It creates a business case for efficiency, data collection, stakeholder engagement, and continuous improvement. Accordingly, it can facilitate communications with utility managers and policy makers regarding these system/business needs.

This chapter is based on the paper entitled “Collectively Re-envisioning the Water Utility Business Model” by Rebecca Dziedzic and Bryan Karney, submitted to Water Resources Management. By discussing the broader issue of the disconnection between user and utility, it
addresses the specific concerns of each, and proposes solutions, especially for the City of Guelph.

4.1 The Water Utility Business Model and the Role of Stakeholder Feedback

The business model, although originally a business tool, can be applied to public policy development, specifically to those aspects related to the provision of services with a strong economic dimension and which require long-term investments, such as water infrastructure. Analogous to businesses, utility managers, private or public, often aim at creating value in a sustainable manner. Value is herein being defined holistically to signify more than financial gain, but to be held in high regard. According to Osterwalder and Pigneur (2010), “a business model describes the rationale of how an organization creates, delivers, and captures value”. Values may be quantitative (e.g., price, speed of service) or qualitative (e.g., design, customer experience). Osterwalder and Pigneur (2010) describe a business model through nine basic building blocks:

- customer segments – different groups of people or organizations an enterprise means to reach or serve;

- value propositions – bundles of products and services that create value for a specific customer segment;

- channels – how a company communicates and reaches its customer segments to deliver a value proposition;

- customer relations – types of relations a company establishes with its customer segments;

- revenue streams – how a company generates revenue from different customer segments;

- key resources – key physical, financial, intellectual, or human resources that allow for creating value propositions, reaching customer segments, and earning revenue;

- key activities – essential activities for making the business model work;
• key partnerships – network of suppliers and partners and

• cost structure – costs incurred to operate a business model.

Utilities deliver water to a plethora of customers who use it in a variety of ways. Boyle et al. (2011) state there is no “average user”. Thus, the customer base should seldom be treated as a single homogeneous mass. Rather, utilities should implement data mining and personalization techniques to identify groups of customers, create a profile of these, and tailor utility policies, rate structures, and programs to best fit them.

Water users increasingly expect higher quality water at lower prices, and sophisticated services as offered by electricity utilities (Heller and Gertsberger, 1999). Yet, water providers must also maintain cost-competitiveness in order to retain control of their business. In exchange for a portion of the industry’s economic security, the practices of privatization, outsourcing, and managed competition promise increased efficiency, which does not always ensue. Heller and Gertsberger (1999) believe the water industry may represent the last stronghold of the monopolistic public utility and is likely to remain so because water production and distribution are strongly bound together.

Whether it is the government, a private company, or a board of citizens, such groups perform a task on behalf of others. In the principal-agent theory, the principal engages an agent to perform a task on the former's behalf, which involves delegating decision-making authority to the latter. The agent, however, might not have strong incentives to act in the best interest of the principal. Therefore, institutional arrangements must be created to establish such incentives (Prosser, 2005).

The complexity of water distribution systems sometimes creates ambiguity about who is the principal and who is the agent. Amit and Ramachandran (2010) discuss water pricing within a principal-agent framework where the water utility (principal) is not able to choose the consumer's (agent) action directly, but can only influence it through incentive mechanisms that penalize excessive consumption through higher costs or reward conservation. From another
perspective, water is a public good and utilities (agent) are responsible for treating and distributing this resource sustainably, which is in the best economic, social, and environmental interest of the user (principal). That does not mean, however, that users act in their own best long-term interest either. Water pricing, for instance, can influence consumers to use more water than is sustainable, or at least fail to curb excessive use. There may not be appropriate incentives in place for water users to reduce consumption, nor for utilities to establish these, particularly when revenues are related to water use.

Moreover, the interdependency between users leads to issues associated with externalities, commons, organization of collective enterprises and public regulation. Such circumstances require the collaboration of stakeholders and application of collective decision rules (Ostrom and Ostrom, 1972). Sproule-Jones et al. (2008) emphasize that in order for decisions to be made, for policy-makers and analysts to ensure sustainability, a fundamental understanding of the properties of water and its multiple uses is essential. According to Whelton et al. (2007), an important resource for water utilities and one that is often overlooked is customer feedback. Users, located throughout the system, automatically and continuously monitor water quality, public health, and the state of infrastructure. Benefits of proactive customer monitoring programs in other industries include increased customer loyalty, better process control, improved product quality, and protection of the company's public image.

In the present study, a survey was developed and conducted with residential water users in the City of Guelph, ON, Canada, regarding expectations of service to inform future utility plans in various areas, different aspects of the business model, such as user characteristics, infrastructure, conservation programs, water supply alternatives, communication and feedback, cost coverage, and rate structure.

In the water sector various user surveys have been conducted to assess current performance in a specific area, or willingness to effect change. Aini et al. (2001) surveyed water users regarding water crisis management. Questions covered user satisfaction, coping strategies, and effect of crisis on user behavior. Yurdusev and Kumanhoglu (2008) surveyed residential water users on
the frequency and types of water use and willingness to conserve water in order to estimate domestic water saving potential. Silva et al. (2010) studied the correlation between conservation and utility communication strategies. Conrad et al. (2012) assessed public perceptions and preferences of water demand management. Tapsuwan et al. (2014) focused on household willingness to pay for decentralized water systems. Franceschini et al. (2010) interviewed customers and authorities on water and sewage service quality indicators (reliability, responsiveness, competence, access, communication, credibility, security, understanding, tangibles).

On a global scale, the World Economic Forum Global Risks Report, which is developed from a survey of over 1,000 experts from industry, government, academia, and civil society, revealed that water supply stresses are considered highly likely of having a large risk of impacts. It is considered more likely in the next 10 years than major systemic financial failure, yet this having a slightly smaller impact (World Economic Forum, 2013). The Royal Bank of Canada (2013) conducted a survey of almost 2,300 Canadians regarding water attitudes. Results were weighted according to gender, age, region, and community size in order to reflect the composition of the Canadian population. Canadians were found to rank the economy as the most important national issue, while water pollution and supply were one of the lowest. Concern over the quality of surface water and the long-term supply of fresh water, however, was found to be high. Ten years from now, Canadians were found to expect the following to be the greatest water-related issues, in decreasing order of importance: water pollution, safety of drinking water, state of the water supply system, shortages of drinking water, state of waste water treatment systems, flooding caused by extreme weather, and state of storm water systems.

In the City of Guelph groundwater is currently the primary source of water. Recent analysis by the local municipal utility has confirmed, however, that the existing water supply capacity will not meet future needs. The city currently has a largely middle-class population of around 120,000 inhabitants, within an area of approximately 86 km². Although population has consistently grown, recent conservation initiatives have reduced residential consumption to nearly 180 liters per capita per day. Residential water use represents about 55% of total
consumption, while single-family detached households represent nearly 70% of this share. Within the industrial, commercial, and institutional sectors, the largest water consumers are manufacturing properties, distilleries, office buildings, shopping centers, post secondary schools, and hospitals.

4.2 User Expectations of Service in Guelph

4.2.1 Objectives

While the City of Guelph has already conducted surveys about water user opinion on programs and by-laws, the proposed study assessed system-wide expectations in order to gauge and improve the correlation between user and utility concerns. The research is intended to inform the City’s current Water Supply Master Plan Update, which seeks to update the Water Supply Master Plan components related to public consultation, population and water demand projections, water supply capacity, water supply alternatives, and implementation recommendations.

4.2.2 Methodology

Questions fall under eight user-related categories: demographics, characteristics, awareness, concerns and issues, initiative and motivation, priorities, communication, as well as business model - water supply and rate structure alternatives. The categories were defined to represent different areas of the water systems. Questions were adapted from previous studies in order to allow for the comparison between surveys as well as developed for the present survey, given its broader theme and the City of Guelph’s specific issues.

The complete survey and the references for the questions adapted from other surveys are shown in Appendix A. The survey is made up of 31 questions, takes about 15 minutes to answer and comprises five types of questions: open ended, yes or no, multiple choice, ranking, and rating. Users are not asked about their views and values, but rather of their behaviour and preferences.
Issues are addressed differently in more than one question to ensure consistency and assess the possibility of misinterpretation or bias.

Respondents were classified according to their demographics and user characteristics. These were correlated to the other answers in order to evaluate the relation between user characteristics and other parameters. Because frequencies were found to be low in various questions, Fisher’s exact test was applied to the analysis of the contingency tables. If a p-value of less than or equal to 0.05 was found, the null hypothesis, equivalent to the independence of answers, was rejected.

The telephone survey was conducted with 400 water users (18 years of age or older) in the City of Guelph, selected to represent all six wards of residents, as defined by the City. The sample size was defined for a margin of error of 0.05 and $p$ equal 0.5, where $p$ is the population proportion parameter. A market research firm appointed by the City, OraclePoll, completed the calls in March 2014. Although a research firm will have more experience in conducting surveys and more personnel to complete them, reducing project duration and costs, errors can occur. The data analysts receiving the survey results, whether at the utility or in this case external researchers, must review the data and be aware of indications of error, such as unexpected answers, identical answers to open ended questions, and very high correlations.

4.2.3 Results

Demographic information of the water users collected through the survey was compared to the most recent census data available, Statistics Canada (2012) for the Guelph metropolitan area. This allowed for an investigation of the differences between sample and population, as well as the identification of user types that are more likely to participate in such surveys. The percentage of users that do not live with children, reside in detached houses, are 55 years of age or older, and have at least a university degree, is higher within the sample than the population, as shown in Table 4.1. The percentage of respondents shown in Table 4.1 excludes those that refused to answer. While, the rate of refusal for most demographic questions is 5% or lower, perhaps not surprisingly many more (41%) did not disclose their household income category.
This demonstrated that older residents were more likely to respond to the present telephone survey, somewhat skewing the results. Nonetheless, younger water users are represented in the survey, and answers to other survey questions about the water system were always compared to categories of users so as to not misrepresent the population and identify correlations between user types and views. These relations are highlighted hereafter. However, in most cases, answers were found to be independent of user category.

Table 4.1: Comparison of respondent and Guelph resident demographics.

<table>
<thead>
<tr>
<th>Water user characteristics</th>
<th>% Respondents</th>
<th>% Guelph residents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live with children</td>
<td>33</td>
<td>61</td>
</tr>
<tr>
<td>Own residence</td>
<td>93</td>
<td>69</td>
</tr>
<tr>
<td>Detached house</td>
<td>81</td>
<td>63</td>
</tr>
<tr>
<td>Above 55 years of age</td>
<td>55</td>
<td>31</td>
</tr>
<tr>
<td>University degree</td>
<td>59</td>
<td>31</td>
</tr>
<tr>
<td>Income above $100,000</td>
<td>47</td>
<td>26</td>
</tr>
</tbody>
</table>

The majority of respondents, 63%, are aware that their drinking water comes from groundwater wells. Although 36% cannot estimate how much water they use, approximately half of the remaining respondents correctly estimated the magnitude of their water use. Awareness concerning the components of the water bill is also low. Respondents consistently identify certain components. In decreasing order of awareness these are: drinking water (85%) and wastewater treatment (80%), maintenance (70%), infrastructure (65%), resource protection and conservation (42%), and storm water management (38%).

Table 4.2: Respondent awareness and performance rating of water system components.

<table>
<thead>
<tr>
<th>Water system component</th>
<th>% Awareness as bill component</th>
<th>% Average or Above</th>
<th>% Don’t know</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment / Quality</td>
<td>85</td>
<td>88</td>
<td>3</td>
</tr>
</tbody>
</table>
This is not always consistent with responses regarding performance in these areas, as revealed in Table 4.2. Even though the majority of interviewees were not aware of how they pay for conservation programs, 61% rated these initiatives as average or above average. Awareness of infrastructure as a bill component is higher, however respondents are less informed about issues related to its performance.

Answers about the affordability of water services vary, and are slightly skewed towards “poor”. Pricing to cover full costs is better rated. However, nearly 40% of users did not know how to evaluate cost coverage. In both cases, low pricing and failure to cover costs, a potential increase in billing could be implied, something fewer users would agree with. When asked to assess different rate options, the majority (53%) agree with the current approach in the City of Guelph, where all water users pay a single rate per cubic meter. Nonetheless, various users also agree with increasing block rates, 53%, and different rates according to user type, 61%. Individuals with higher incomes agree more with this water rate scenario in which different types of customers, such as industrial, commercial, and residential, are charged different rates. Furthermore, the majority of interviewees, 57%, disagree with flat fees, through which users pay the same total fee, regardless of use. Compared to permanent residents, seasonal or part time residents agree even less of the time with a flat fee structure. Overall, the majority of respondents agree with modifying the water rate structure so that prices better represent costs. Therefore, the City of Guelph should review its water pricing scheme accordingly.

According to the participants, the top issues facing Guelph water systems today, are water scarcity (25%), threats to water quality (24%), aging infrastructure (15%), and costs (14%), as indicated in Figure 4.1. In the City of Guelph, the use of water from limited groundwater supply has prompted water conservation initiatives and studies by the utility, such as the current
assessment of different water supply alternatives as part of the Master Plan Update. These have led to numerous news stories and greater awareness of the issue. When asked to predict the biggest water related problem ten years from now, interviewees overwhelmingly (70%) selected water scarcity. Therefore, Guelph water users rank water issues differently than the average Canadian, as assessed by the Royal Bank of Canada (2013). Across Canada, the greatest concern is water pollution, whereas in Ontario, it is the safety of drinking water.

Figure 4.1: Most important issues presently facing Guelph’s water system according to respondents

Scarcity is also the top motivator for water conservation in the City of Guelph. 52% of interviewees identified water availability as a personal reason for conserving water. Other top motivators include costs (52%) and moral responsibility (43%), shown in Figure 4.2. These answers do not sum 100% because respondents could list up to three reasons. The majority, 68%, affirm they try hard or very hard to conserve water. A significant percentage, 20%, however, believe to have already done everything they possibly could to conserve water.
Respondents listed various actions they have completed to increase residential efficiency over the last two years. These have focused on installing water efficient appliances (dishwashers, clothes washers) and devices (faucets, aerators, shower heads) indoors as well as reducing lawn watering. Less attention has been given to water efficient landscaping (replacing grass with water wise plants, planting trees), rain water use, and checking for leaks within the household, strategies which could be promoted in the future to further reduce water consumption.

In times of scarcity, respondents believe that water use for household indoor needs, municipal operations, wildlife and the natural environment should be top priorities. This is reflected in their opinions on water restrictions. Interviewees agree more with restrictions on private lawn watering, as well as on use by industry or business. In contrast to previous responses, answers to these questions were found to be dependent of user type. Households that directly pay their water bill, compared to other users whose water is included in rent or condo fees, agree more with restricting the amount of water that can be used on private lawns or landscapes, and agree less with allowing local natural reservoirs to be depleted. Although depleting local natural reservoirs would temporarily supply more water it would affect local ecosystems.

In order to increase water supply or decrease future demands, the majority of interviewees agree with increasing conservation (80%), restricting water use for new developments (68%), improving (76%) and building (56%) new infrastructure, as well as procuring new groundwater
sources inside (69%) and outside the city (51%). However, respondents aged 55 and above, compared to younger interviewees, agree less with using water from new groundwater sources outside the city. Answers regarding the use of water from surface water sources, i.e. Eramosa River, Speed River, or Guelph Lake are divided.

Most customers (71%) agree that Guelph Water Services notifies users of changes to water servicing in their area. Although only 40% agree that they are informed of the City of Guelph’s plans for providing water and their opportunities to participate in the discussion, 22% did not know how to respond to this question. Opinions on customer level of involvement in decisions are divided. Therefore, interviewees are more aware and involved in receiving communications from the utility, rather than in providing feedback.

According to respondents, the best ways to reach them with information is through water bill inserts, newspapers, emails, and the Guelph website. For providing input, they prefer surveys, open meetings, and focus groups. These users, however, are obviously partial to surveys. Furthermore, individuals with higher incomes were found to agree less with communicating through focus groups. This highlights the need for applying different communication methods in order to reach all user types and receive their feedback.

Given these results, in order to increase awareness, the City of Guelph should improve its communication with water users, such as through bill inserts, one of the media preferred by the respondents, or perhaps through a new online portal, where messaging could be more easily customized. This would also be useful for receiving user feedback. With an individual customer login and password, the number of unverified responses could be decreased, one of the main issues of online surveys. While the city has had more experience and success in reaching customers through telephone surveys, other strategies are necessary to reach all customer segments, as shown by the responses.
4.2.4 Discussion and Business Connections

The business model of water utilities, specifically of the City of Guelph, and how the present survey applies to its analysis are discussed hereafter. The definitions of business model components explored below are derived from Osterwalder and Pigneur (2010) whereas the observations regarding water utilities and discussion of the ramifications of the survey results are of the authors.

4.2.4.1 Creating value for customers

In order to better satisfy customers, businesses group them into separate segments, especially if their needs, distribution channels, types of relationships, profitabilities, and willingness to pay for distinct aspects of the offer differ. Many water utilities, however, assume a mass market, focusing on one large group of customers with broadly similar needs and issues. Although the City of Guelph has detailed information on consumer land use and water usage this is for the most part not used in improving the business model. Customer segments are not distinguished in the cost structure, for instance. Survey results show however that a mass market cannot always be assumed, and the segmentation of customers has the potential to improve other business components.

For a conventional business, the value proposition is the reason why customers turn to that company. Most Canadian water utilities, however, do not have a direct competitor since the municipality runs them and functions more or less as a regulated monopoly. Water, depending on the end use, yet in limited quantities, could alternatively be sourced from bottled water, private wells, or rainwater. Nevertheless, because water is a limited resource, the goal of the utility should not be to increasingly sell more water. Indeed, motivated by dwindling groundwater and high costs of alternative sources, the City of Guelph offers rebate programs for water efficient appliances and fixtures, as well as rainwater harvesting and greywater reuse.

Competition can lead to greater value creation. Elements that contribute to customer value creation include: newness, performance, customization, “getting the job done”, design,
brand/status, price, cost reduction, risk reduction, accessibility, and convenience/usability. Examples of how these are relevant to water services include:

- newness: incentives for new water efficient or water free appliances;
- performance: increased water quality;
- customization: decentralized solutions for users with special requirements;
- “getting the job done”: consistent delivery of sufficient good quality water;
- design: improved utility building aesthetics, clear and engaging written communications;
- brand/status: customers may pay a premium for a certain brand of bottled water
- price: affordability;
- cost reduction: conservation and rebate programs
- risk reduction: frequent maintenance, timely emergency responses;
- accessibility: provide tap water for all consumers;
- convenience/usability: install public water fountains in parks and busier areas of the city.

The majority of survey participants who responded to questions regarding system performance agreed that it is above average in the City of Guelph.

If competition is lacking, such as in water utilities, there should be incentives for creating value and avoiding poor performance (environmental, social, or economic). Regulations can establish minimum standards, benchmarks, and goals. The Ontario Water Opportunities Act (2010), for instance, requires municipal service providers to submit municipal water sustainability plans and enabled the Ministry of the Environment to define performance indicators and targets. However, details of these plans and metrics are not yet fully specified.
In the piped water markets of England and Wales, competition has been introduced through three channels: inset appointments, cross-border competition, and common carriage. The first allows new entrants in the market to supply certain customers in a defined geographical area. Cross-border competition allows customers located at the border of a supply area to purchase water from an existing neighboring utility. Common carriage refers to the shared use of assets, such as the pipe network. The network owner, thus, charges an access fee to its competitors. However, the role of competition is currently still minimal. Some of the primary reasons are that incumbents can defend their monopoly positions by charging high access prices, building new treatment facilities is costly, issues arise from mixing different water qualities, and there are limitations to transporting water over long distances (Foellmi and Meister, 2012).

In Canada, provinces bear the constitutional responsibility for freshwater management. The range of business models legally permitted varies by province and Ontario has experienced the most pronounced restructuring. According to Bakker and Cameron (2005), this process was motivated by three main developments: a devolution of service provision from the provincial to the municipal level; deregulation of the electricity sector and break-up of the Public Utility Commissions which provided electricity, water, as well as other services to rate payers; and the creation of new regulations and legislation for water supply following contamination incident in Walkerton, Ontario. These initiatives also overlapped with a trend towards commercialization of the sector, which supported the creation of legislation that allows for new business models, such as corporatized public utilities.

However, private sector participation in water delivery does not always yield the promised results. Various municipalities have renounced the private sector involvement in recent years, such as Atlanta, Hamilton, and Paris (Ohemeng and Grant, 2011). In 1995, the City of Hamilton, after facing an economic downturn, awarded Philip Environmental Inc. a 10 year contract to operate the region’s water systems. Notwithstanding, during this period equipment was poorly maintained and a significant number of employees was laid off. Allowing for private sector involvement did not motivate competition in this case since a private monopoly was created.
Because water is usually conveyed through a complex looped network of pipes, quality, flow, and pressure conditions at one point can influence the entire system. This undermines the ability of new suppliers to enter the market unless they become responsible for one component of the water supply, or offer decentralized solutions. The latter is not only beneficial to potential market entrants but to existing municipal utilities as well, as it allows for greater tailoring of services to specific customer segments. For instance, decentralized pumping, storage, treatment, or rainwater collection could reduce system wide costs of delivering to all what meets the requirements of few. Noll (2002) believes that water systems with multiple reservoirs could be made competitive by emulating electricity grids, treating each reservoir akin to an electricity generator and directing water through a decentralized wholesale market.

The value proposition of the Guelph water utility, as many other Canadian utilities, involves a bundle of services, i.e. water treatment and delivery, wastewater collection and treatment, stormwater collection, and natural resource protection and conservation programs, as well as one-time offers such as the installation of new services or inspection infrastructure in case of alterations. Responses to the survey, however, revealed that most water users in the City of Guelph are not aware of all the services they receive and pay for. Therefore, the utility, as a business, must better inform users of offers and highlight their “competitive advantage”, such as by better distinguishing between cost components in the water bill, informing customers of latest efficiency strategies as well as city wide outcomes, and championing users that conserve most water.

4.2.4.2 Collaborating with stakeholders

Customer channels can be used to raise awareness among users about the water utility’s services. These channels refer not only to product or service distribution but also to communication. Customer channels have five phases: awareness, evaluation, purchase, delivery, and after sales. The right mix of channels for each of these phases enhances customer experience. Users may be contacted through owned or partner channels, directly or indirectly. Because Canadian water utilities are municipally owned, distribution and communication are mostly led in-house.
Nevertheless, such as is the present case, other researchers or consulting groups, with more expertise, experience, or cost effective solutions, can lead surveys, focus groups, and meetings.

Collaborations or outsourcing can also be sought for decentralized solutions, such as residential water conservation strategies. Information about water use and conservation can also be disseminated through partnerships with schools, home improvement stores, malls, contractors, etc. Survey respondents, however, were found to prefer direct communication from the utility. This probably depends on the type of information being conveyed, whether the message relates to future lawn watering restrictions or best water conserving fixtures, for instance. This was not distinguished in the survey. Thus, future studies should differentiate between types of communication in identifying preferred channels.

In addition to improving communications, key partnerships are formed to optimize the business model, reduce risk, or acquire resources. Collaboration between water utilities, such as through provincial alliances, creates a platform for sharing of knowledge, experience, and best practices. Partnerships with technology providers, such as pumps, water treatment equipment, and operations optimization software can improve performance. Policies and strategies of municipally owned water utilities in Ontario are increasingly favouring such partnerships, such as the Ontario Water Works Association, Ontario Clean Water Agency, Southern Ontario Water Consortium, and the Ontario Water Technology Acceleration Project.

Customer relationships range from personal to automated and are driven by business motivations: customer acquisition, retention, or upselling. These motivations are less relevant for water utilities, especially for those that do not experience competition. Since water is an essential and limited resource, users need to acquire it, yet with a certain restraint. Therefore utilities must navigate this balance between needs and wants, maintaining customer satisfaction through a relation that most resembles customer retention. The issues that most concern water users in the City of Guelph and that need to be addressed by the water utility are scarcity, aging infrastructure, and costs, thus related to key resources, cost structure, and revenue streams.
For water utilities, customer relationships are mostly centered on self-service, i.e. the business provides the means for customers to help themselves. In case additional information is needed or in the event of an emergency, personal assistance is employed. Nevertheless, as highlighted by the survey, distinct customer segments require different types of relationships or messaging. Guelph water users prefer to receive information through water bill inserts, newspapers, emails, and the Guelph website. These can be customized according to user awareness, concerns, motivations, and priorities, as identified in the survey.

The fact that water use is self-service does not impede conservation. Pricing, rebates, and community awareness programs can reduce consumption. Messaging can also be used to inform users of their consumption more frequently than once every billing cycle, such as in the City of Guelph. As automatic meter reading becomes more common, users could be alerted when their consumption exceeds a certain goal or a pricing block, similar to notifications from Internet service providers regarding data usage. This would increase user awareness of personal water consumption, which was found to be below 40% for survey respondents in the City of Guelph.

4.2.4.3 Transforming resources into revenue

Although the key activity of water utilities is production, related to the design, operation, and maintenance of the infrastructure, data collection and analysis also plays an important role. Infrastructure performance, consumption, and stakeholder data can be used in optimizing operations, defining customer segments, billing, and broadly improving customer relations. Osterwalder and Pigneur (2010) state that key resources can be physical (infrastructure, equipment), financial, intellectual (brands, proprietary knowledge, copyrights, patents, databases), or human (experience, skills). However, the key resource in this case is obviously natural: water. This should motivate stewardship and long term planning by utilities concerning this indispensable resource to the business.

This type of strategic planning is crucial for the City of Guelph because of its impending groundwater shortage. Other important resources include the physical infrastructure for treatment, pumping, storage, and distribution. Because the business is not extremely knowledge-
intensive nor structured around creativity, human resources are not preeminent. Intellectual resources, such as customer databases and partnerships with researchers or technology providers, are nevertheless valuable for selecting and applying water conservation solutions. Financial resources, specifically reserve funds for capital expenditures are imperative in order to address infrastructure funding gaps, which have grown in North American water utilities, including the City of Guelph.

Revenue streams represent the earnings generated from each customer segment and two types exist: transaction revenues, resulting from one time payments such as the installation of services, and recurring revenues, such as from ongoing water bill payments. In the first case, revenue is generated from the licensing of the water connection, whereas in the latter it is generated from water usage fees. From an economic perspective, water utility revenue should cover total costs, whereas socially prices should allow for basic use as well as represent costs incurred by each customer segment. Still, from an environmental standpoint they should inhibit excessive consumption.

Given these goals and the nature of the market, the applicable pricing mechanisms include the following:

- product feature dependent: price depends on the value proposition features, e.g. quality, pressure;
- customer segment dependent: price depends on the type and characteristic of a customer segment, e.g. sector, water usage tier,
- volume dependent: price as a function of the quantity purchased; and
- yield management: price depends on inventory and time of purchase, such as local water availability.

Respondents of the survey were found to agree with customer segment and volume dependent pricing mechanisms, strategies that should be pursued by the City of Guelph. Other options are
less common for water utilities and would require greater research as well as stakeholder analysis.

The cost structure of a business model describes its most important expenses, and generally falls between two extremes: cost and value driven. The first focuses on minimizing costs wherever possible whereas the latter is concerned with value creation and highly personalized offers. Because of the strict safety standards, strong connection between treatment and distribution, and cultural aversion to privatization of water systems, a lean cost structure with extensive outsourcing is not ideal. Delivering an extremely customized, luxurious service is also not the goal of water utilities. Nonetheless, customization can decrease costs such as by reducing excessive pressures. Water utilities must, thus, balance the costs of complex water networks with individual user demands.

The present survey assessed these individual expectations and together with other economic, environmental, and social analyses was used in updating the City of Guelph’s Water Supply Master Plan. Given the current restricted availability of water in the City of Guelph, the main survey questions that informed this update were related to the conservation and procurement of new water sources. Most users support increased conservation and procuring new groundwater sources within as well as outside of Guelph. Using water from local contaminated sources, received more negative reactions. These options, however, cannot be fully discussed within a survey and must be assessed based on multiple financial, social, and environmental objectives. If, for instance, the contaminated source could be adequately treated for human consumption and still represented an economical alternative, the public preconception could be overcome through utility engagement.

4.3 Conclusion

The business model perspective motivates a systems approach and warrants a deeper understanding of the users and the services or products they require. For water utilities, this
means recognizing that water can be used in multiple ways, providing distinct services to diverse customer segments that value water differently. Stakeholder integration allows for decisions to be made with the users, for the users.

The present study conducted a survey with residential water users in the City of Guelph, ON, Canada, regarding expectations of service. Results of the survey highlight user concern with the scarcity of water in the city, an issue that has been regularly addressed by the local utility and is the focus of the latest Water Supply Master Plan Update. Other major issues identified by the respondents were water quality, aging infrastructure, and costs. The reasons for why these also concern water users in Guelph, and how they could be addressed should be further explored.

In order to avert scarcity, respondents agreed with procuring water from new groundwater sources, as well as setting restrictions for water use in private lawns, industries, businesses, and by future growth. Interviewees also agreed with changes to the water rate structure: increasing block rates, and differentiating by user type. Recently, few respondents have undertaken water efficient landscaping, rainwater use, and leakage checks, actions that could be promoted to further reduce water consumption.

Although only residential water users were interviewed, industrial, commercial, and institutional opinions would likely differ and should be included in the decision making process as well. By comparing the collected information to Statistics Canada (2012) census demographic data, it was found that the older population (55 years of age and above) was more likely to participate in the telephone survey. Therefore, different feedback channels should be frequently used in order to gain input from the different customer segments.

Accordingly, the City of Guelph water utility could largely benefit from better distinguishing between customer segments in its business model and how it affects its value proposition, customer relations, channels, cost structure, and revenue stream. Partnerships, such as in the present research, should be further sought by water utilities to identify and resolve issues collectively. Communication channels can be used not only to contact users regarding billing or new programs, but also to receive feedback and increase consumer awareness.
The present survey was designed for the City of Guelph but many of the questions are relevant to most water utilities and can be adapted to better represent specific utility practices and issues. The survey is meant to be conducted during operations, for master planning purposes, such as was the present case, or for monitoring system performance on a more frequent basis. Because the questions relate to various components of the system, they motivate a broader analysis. Furthermore, the business model perspective applied in the discussion of the results sheds new light on existing issues, and can lead to novel approaches.
5 Energy Metrics

Based on the literature review in Chapter 2, specifically the LCA of water systems by Stokes and Horvath (2011) and the Electric Power Research Institute (2002) report, it is clear that energy is a key resource for water distribution systems. It is essential in operations and generates significant costs as well as GHGs. Furthermore, in water distribution systems, energy integrates two key system parameters, head and flow, which can be modeled with readily available hydraulic software, such as EPANET. Therefore, metrics can be developed from first-principles that summarize the different aspects of the global energy balance in a water distribution network. Because most utilities retain a hydraulic model of their system for planning and monitoring purposes, the metrics can be easily applied. Furthermore, different from previous studies these assess efficiency at a component level as well, allowing for the identification of specific problematic components or areas.

This chapter is based on the paper entitled “Energy Metrics for Water Distribution System Assessment: A Case Study of the Toronto Network” by Rebecca Dziedzic and Bryan Karney, submitted to the Journal of Water Resources Planning and Management. The goal of this chapter is to define descriptive energy metrics that can be applied in the sustainability assessment of different water distribution systems and scenarios. It directly addresses the issues of network energy inefficiency, high energy costs, and greenhouse gas emissions. Therefore, it draws attention to the problems caused by aging infrastructure, pipe breaks, and high pressures. The metrics established and explained here are further used to develop performance metrics in chapter 6.

5.1 Introduction

Central to the water-energy nexus is the fact that electricity is essential for supplying water, and water is an important energy carrier, used in generating electricity. Both water and energy are key inputs to a great many human activities and are important ecosystem services. Given the
increasing global population and limited water availability, as well as high electricity costs, the need for more efficient consumption is pressing. Furthermore, water distribution is usually at least partially powered by fossil fuels, the combustion of which emits greenhouse gases and contributes to both resource depletion and climate change.

Life cycle analyses of water infrastructure (Stokes and Horvath, 2011) have indicated that the operational phase is largely responsible for environmental impacts, viz., 67% of greenhouse gas (GHG) emissions. Energy use, specifically, contributes to 50% of total GHG emissions. Furthermore, according to the Electric Power Research Institute (2002), approximately 80% of municipal water processing and distribution costs stem from electricity use. Regardless of network size, the primary use of this electricity is for pumping treated water to the distribution system, which represents about 80 to 85% of the total electricity consumption for surface water systems. Groundwater systems generally require 30% more electricity (Electric Power Research Institute, 2002).

In a broader context, water and wastewater services represent the single-largest source of electricity consumption in many municipalities, comprising between one to two thirds of municipal utility electricity costs in Ontario (Maas, 2009). Therefore, reducing energy consumption and consequent GHG emissions in water distribution has large potential benefits on a variety of scales. Racoviceanu et al. (2007) established three major reasons for restricting the analysis of water systems to energy use and GHG emissions. First, energy use and GHG emissions occurring during the construction and demolition phases can be considered impulse actions; there are fewer opportunities to reduce impacts from these stages relative to those throughout operation. Second, construction and demolition energy use and GHG emissions are little affected by alternative treatment technologies or abatement strategies. Third, as mentioned, operations constitute the majority of the energy and material intensive phase.

According to Kumar and Karney (2012), energy is a practical and universal abstraction, for it is not only a commodity, but also a conceptual framework, in which usefulness and viability, among other characteristics, can be gauged. Additionally, since energy is conserved and can be
accounted for throughout the system, similar to currency, it has the potential to be used as a measure of a service’s value. Specifically in water distribution, energy has the additional capacity of integrating the two primary products of the system, and which control design: water flow and pressure. The amount of energy associated with water distribution, and its different forms, can be estimated with easily available simulators such as EPANET.

Pelli and Hitz (2000) define indicators of system energy use though they are not based on hydraulic modeling, however. Rather, they are calculated using average differences in elevation and pumping requirements. Boulos and Bros (2010), instead, model network energy efficiency and carbon emissions. Energy losses are classified as diffuse (friction), discrete (valves), or tap (customer connection). Gay and Sinha (2012) also model network energy use, and compare minimal, ideal, and actual energy use. Cabrera et al. (2010) further distinguish between energy forms in the network: total energy input, dissipated, lost through leaks and delivered. Energy efficiency indicators are defined according to ratios between energy supplied, energy lost, and useful energy or minimum required useful energy.

All of the aforementioned studies evaluate energy efficiency at an aggregated system level. Cabrera et al. (2010) recommend that the energy balance be calculated for one year in order to improve comparisons between systems. While these indicators can be used to assess modeled improvements to the systems, they do not reveal where and which types of modifications are most beneficial. Although the forms of energy use are distinguished the system is largely still seen as a black box.

Pflanz et al. (2009) convincingly assert that there is no single answer for every water system. The specific design, operation, and maintenance of each system must be analyzed with respect to system interactions, while balancing not only energy use, but costs, greenhouse gas emissions, infrastructure performance, and safety as well. Clearly modeling is instrumental in assessing the system in detail.

The present approach proposes metrics that can be used to assess the temporal variation, as well as the balance, of energy flows at both a component and network level, in order to support
system planning, and specifically activities like the optimization of operations, the choice of pump and pipe renewal strategy, and issues cost allocation. The metrics are applied to a case study of the Toronto water distribution system and mapped, for which energy costs and greenhouse gas emissions are calculated. This motivates a discussion of potential improvements, as well as applications and limitations of the metrics given real utility practices.

5.2 Methodology

5.2.1 Metrics

Energy is needed to move water through the distribution system, while meeting expectations and operational goals as well as minimum regulated requirements. Even though generally well known, for clarity of later developments we review the essence of an energy formulation for a water system briefly here. In essence, energy plays three essentially unavoidable roles in a water system: to overcome elevation differences, to compensate for energy losses, and to meet operating pressure requirements. Energy can be supplied as gravitational potential through relative elevation of reservoirs or tanks or, more commonly, through pumps. Part of this mechanical energy, however, is irreversibly dissipated, being converted to thermal energy by friction throughout the system. Furthermore, there is a fourth energy term that is definitely unwanted: energized water is lost through leaks. Thus, only a portion of the energy that enters the distribution system is delivered to the consumer, and this inefficiency depends on characteristics of the infrastructure and its operation. Energy can be calculated in several ways but can be thought of as a time integral of power, and consequently of head and flow, as (5.1),

\[ E = \int_0^t P \, dt = \int_0^t (\gamma H Q) \, dt \] (5.1)

where, \( P \) is power (W); \( \gamma \) is specific weight (N.m\(^{-3}\)); \( H \) is the associated change in head (m); \( Q \) is flow (m\(^3\)/s); \( t \) is time (s).
Modeling results almost universally unfold over a sequence of time steps. Then, an average energy flow, \( E \), may be considered over the given period, \( t \), as indicated by (5.2), where the overbar indicates a time average.

\[
E = \bar{P}_t 
\]  

(5.2)

Energy supplied to the water distribution system can be evaluated by the sum of its different forms as it passes through and leaves the system, as indicated in (5.3). The pipes and appurtenances constitute a control volume, to which water and energy is supplied, and from which it is also retrieved. Since energy is conserved, energy input equals energy output, an equivalence that can be confirmed as an accounting check, that both sides of the following equation add up to the same values (as was done in the present study).

\[
\sum E_{supplied} = \sum E_{dissipated} + \sum E_{lost} + \sum E_{potential} + \sum E_{delivered} 
\]  

(5.3)

where, \( E_{supplied} \) is energy supplied at pumps, tanks, and reservoirs, \( E_{dissipated} \) is energy dissipated in pipes, pumps, connections, and valves due to friction and inefficiency (Wh); \( E_{lost} \) is energy lost due to leakage of pressurized water (Wh); \( E_{delivered} \) is energy delivered to nodes or tanks in the form of pressure and velocity, including requirements and excess energy (Wh); \( E_{potential} \) is the potential energy established by the difference in elevation between supply and delivery. These terms must be summed over all elements for each time step.

Figure 5.1: Schematic representation of the different forms of energy in a water distribution system with a single reservoir, pump, pipe and tank.
Each of the forms of energy, as dependent upon head, is represented in Figure 5.1. The inefficiency of the pump is not reflected in the energy grade line but is considered as part of the energy being supplied and subsequently dissipated at the pump. Therefore, the energy supplied metric includes the wire power bought from the power company and the energy dissipated metric includes the energy lost due to pump inefficiency.

Significant errors can be incurred if manufacturer curves are used to characterize pumps in the model, and an estimated constant efficiency assigned, without correcting for actual performance. HydraTek (2013) tested 152 pumps currently used in Ontario, Canada, and found that these have, on average, peak efficiencies 9.3% lower than their originally manufactured state. This gap further increases to 12.7% when accounting for operation away from peak efficiency.

The required energy parameters are simply retrieved from hydraulic models. Detailed leakage information, however, is usually only estimated by municipalities. Locating unreported bursts is a cumbersome task, for it requires expensive, specialized equipment, which make it economically and technologically infeasible (Tabesh et al., 2009). Instead, leakage is generally equally distributed throughout the system or by district metering area (Thornton, 2004). This means $E_{\text{lost}}$ would be approximated as a percentage of $E_{\text{delivered}}$. Alternatively, if leaks were modeled, energy lost would be proportional to the product of flow through the leak and the difference in head between the inside and outside of the pipe at the leak location.

The location of the leaks affects energy requirements (Colombo and Karney, 2002), and thus modeled pressures may be higher or lower than in reality than by assumption. The error is inversely proportional to the size of the metered areas in the network, since in smaller areas localized leaks are subject to less severe averaging. Information on pipe material and age can improve the allocation of leaks. Lambert and McKenzie (2002) found that generally private pipe is responsible for more losses than water mains, and leak discharge varies linearly with pressure. Given these relations, the leakage indicators proposed by the International Water Association (Alegre et al, 2000) can be applied to estimating the current and unavoidable real losses of water distribution systems.
Energy dissipated is calculated according to (5.4),

\[ E_{\text{dissipated}} = \gamma \cdot H_{\text{loss}} \cdot Q \cdot t \]  
(5.4)

where \( H_{\text{loss}} \) is head loss (m), which comprises local losses or friction losses, for each valve, pipe, or pump, output from the hydraulic model, and \( Q \) is flow (\( \text{m}^3 \cdot \text{s}^{-1} \)).

Energy delivered and supplied are given similarly by (5.5) and (5.6),

\[ E_{\text{delivered}} = \gamma \cdot (H_{\text{node}} - z_{\text{node}}) \cdot Q_{\text{delivered}} \cdot t \]  
(5.5)

\[ E_{\text{supplied}} = \gamma \cdot (H_{\text{node}} - z_{\text{datum}}) \cdot Q_{\text{supplied}} \cdot t \]  
(5.6)

where \( H_{\text{node}} \) (m) is head delivered at or supplied by the node, depending on the direction of flow, \( Q_{\text{delivered}} \) is flow delivered, \( Q_{\text{supplied}} \) is flow supplied, \( z_{\text{node}} \) (m) is the elevation of the node, and \( z_{\text{datum}} \) is the datum of the network. The net change in energy storage over an extended period should be zero and is not significant in an average network energy metric. In that case energy supplied and delivered by tanks would be equal and would not affect the energy balance. However, the proposed metrics are intended to assess the system’s temporal and spatial variations of energy flows. When considering small time steps, such as the hourly variations analyzed in the case study, storage exchanges affect the energy metrics of the network and must be accounted for.

The elevation, responsible for potential energy, was subtracted from energy delivered so that it could be analyzed separately from pressure. With this approach, energy delivered represents the portion of energy that reaches the consumer and is readily available as pressure and flow. Potential energy is the amount of energy spent to overcome differences in elevation within the network.

\[ E_{\text{potential}} = \gamma \cdot (z_{\text{node}} - z_{\text{datum}}) \cdot Q_{\text{delivered}} \cdot t \]  
(5.7)
The sum of energy delivered and potential indicates the energy requirements of each user. Accordingly, the energy efficiency (5.8) of the system can be gauged by the ratio between the sum of energy delivered and potential, and energy supplied.

\[ e = \frac{E_{\text{delivered}} + E_{\text{potential}}}{E_{\text{supplied}}} \]  

(5.8)

Costs and greenhouse gas emissions associated with energy consumption are proportional to the energy supplied by pumps. Electricity rates vary by hour and season, as do the emission factors of the grid since energy is produced at different generators, operating at different intensities throughout the day. Therefore, apart from the consideration of varying electricity costs, the analysis of hourly fluctuations in GHG emissions can further inform operations (Bristow et al., 2011).

### 5.2.2 Potential Applications of the Proposed Energy Metrics

Water utilities generally retain a hydraulic model to simulate system performance, compliance with pressure requirements, and provision of sufficient fire flow. Therefore, the proposed metrics can be easily calculated without representing great additional computational costs. Because the metrics are computed for each network component and time step, they can be mapped to show hot spots of inefficient energy use. While not replacing detailed studies of operation and maintenance, these metrics and their graphic representation constitute a useful management tool for utilities. The metrics can motivate different responses from the utility, as explored hereafter.

Energy supplied is an indicator of the system’s operating capacity. Energy supplied specifically at pumps is highly correlated to electricity costs and greenhouse gas emissions. Therefore, comparing hourly variations in energy demands, electricity rates, as well as emission factors, and adjusting pumping accordingly, can reduce financial and environmental costs. If pumping energy is high and so are the pressures in an area of the network, adjusting pressure zones should be investigated.
The partition of energy to each final form (dissipated, lost, or delivered) rather obviously implies which types of strategies should be prioritized. Energy hotspots prioritize areas and components for reviewed. For example, if energy delivery to a specific area, or a dead end zone is high, lowering the pump set point or pressure management would be natural. Installing pressure reducing valves increases local dissipation at the valve but reduces energy dissipated and lost through leaks thereafter. If energy lost is high, pipe rehabilitation and replacement should also be studied.

From the perspective of energy consumption, additional benefits might be gained with the extension of pressure management to include the reduction of energy supplied at pumps. Even within the American Water Works Association (1995) recommendations of a minimum pressure range of 21 to 28 m and a maximum range of 56 to 70 m, space for improvement might be found. Alterations to operational standards will undoubtedly affect the manner in which the system functions, however. Depending on system design and current operations, pressure reduction may cause more pump cycling. Frequent cycling of implies the system has inadequate storage and tanks might usefully assist to maintain pressures.

The energy equation (5.1) makes it obvious that high pressures are not the only factor responsible for excessive system energy demands, and that reducing flows in the system could minimize electricity costs. There is a major caveat to this statement, though. Water distribution networks are designed for a set of pressures and demands, and usually operate more efficiently with high demands. This trade-off must, thus, be analyzed, but conservation can also reduce treatment and expansion costs.

Energy potential, as separated from energy delivered, represents the portion of energy used dependent upon the elevation of the customer. This value thus depends on the topography of the system as well as its demands and is more difficult to control. Nevertheless, it indicates that users at higher elevations require more energy, an additional cost that could be included in water rate structures or at least inform future zoning practices.
If a lot of energy is dissipated through pressure reducing valves and the supply is by gravity, the installation of turbines to recover energy should be explored. Otherwise, if flow is pumped, adjusting pressure zone boundaries should also be investigated. High levels of energy dissipation at pumps can motivate operational changes to pump combinations and scheduling or even pump refurbishments and replacements.

Excessive dissipation in particular pipes should prompt consideration of cleaning, lining, or even replacement. Simply from an energy savings perspective this type of rehabilitation is generally only justified for heavily tuberculated pipes, with high dissipation (Walski, 1985). High energy dissipation in pipes has not been shown to increase the probability of failure; however, it is often proportional to parameters that have been related to breakage. Dissipation is directly proportional to high pressures, which can increase the risk of breaks (Rajani and Kleiner, 2001). It is also inversely proportional to pipe diameter, and smaller diameters have been shown to cause a higher incidence of breaks (Kettler and Goulter, 1985). Furthermore, although pipe roughness has not been linked to pipe failure, it increases (and C-factor decreases) with age, the main predictor of breakage (Rajani and Kleiner, 2001). Therefore, energy dissipated per length of pipe can be applied as an indicator of pipe failure. This relation was confirmed by comparing energy dissipated and breakage rate maps in Toronto (Toronto Water, personal communication, 2012).

5.3 Case Study of the Toronto Water Distribution System

The proposed metrics were applied to a case study of the City of Toronto’s water distribution system. The system is comprised of nearly 6,000 km of water mains, 41% of which are over 50 years old, and 7% over 100. Partially due to such aging of the infrastructure, Toronto has a high rate of water main breaks, 21 breaks per 100 km of pipe (City of Toronto, 2012). This has prompted an ongoing leak detection and valve maintenance program. The distribution system currently comprises six pressure zones and more than 470,000 service connections. The model, however, shown in Figure 5.2, contains only trunk water mains (which represent about 10% of total water main length) and demands are grouped into 1582 junctions. This simplification means
dissipation is somewhat underestimated, and energy delivered overestimated. Nonetheless, this greatly decreases the computational intensity of analyses. Furthermore, although Lake Ontario is the sole source of water in Toronto, the model contains four main reservoirs, corresponding to the city’s four water treatment plants: R.C. Harris, R. L. Clark, F. J. Horgan, and Island Water.

![Skeletonized Toronto water distribution network.](image)

Toronto Water provided the hydraulic models, in EPANET format, used in the case study. Two scenarios, maximum demand day (July 4th, 2011) and minimum demand day (January 21st 2012) were simulated. Both have an extended period simulation of 24 hours, allowing the visualization of operations throughout the day, and the fluctuations in supply and delivery. Each model was based on the demands of the specific day, and calibrated, also by Toronto Water, according to tank pressures. Minor changes were made to the infrastructure from July to January. One
junction, five pipes, two pumps, and five valves were added, to the 1603 nodes and 1833 links in
the first scenario.

Because the modeled scenarios correspond to specific days of operation, the electricity rates and
the GHG emission factors of those specific days were applied. Electricity rates were obtained
from the Ontario Energy Board historical time of use energy prices (Ontario Energy Board, 2012). GHG emissions from nuclear and coal generation were based on data from Ontario Power
Generation (2010), whereas emissions from natural gas plants were estimated with U.S.EPA

5.3.1 Results and Discussion

5.3.1.1 Summer and winter scenarios

The energy metrics described in (5.3) to (5.7) were applied to the analysis of two scenarios,
summer (July 2011) and winter (January 2012), of the Toronto water distribution system.
Because leaks are not included in the Toronto model, the sum of energy dissipated, potential, and
delivered equals total energy supplied. The lost portion is not disaggregated from other metrics,
and can be considered a percentage of energy delivered, even though this assumption has its
flaws, as discussed earlier. Particularly in Toronto, the percentage of non-revenue water is
approximately 10% (Toronto Water, 2005).

On average, approximately 28% of energy supplied is delivered to junctions, and 72% is spent in
reaching them. Accordingly, 28% of energy supplied to the system is used in meeting pressure
requirements, 35% in overcoming differences in elevation, and 37% in overcoming friction.
Figure 5.3 shows the hourly variation of energy dissipated, delivered, and potential. In the
summer scenario, the increased demands generate higher energy requirements. However, the
percentage of energy delivered is also higher. The lowest efficiency is observed at 5 am on the
winter day, 49%, and the highest at 8 pm on the summer day, 71%.
Because all of Toronto’s water comes from Lake Ontario, reservoirs are at the lowest elevations of the network. Therefore, gravity flow is not prevalent, and pumping is fundamental. The calculations, however, consider the clearwell at the water plant as the source. Dissipation through the treatment plant is not included in the metrics. Tanks “supply” between 5 and 15% of energy requirements. Pumps are responsible for 80 to 90% of energy supply. However, 47% of dissipation already occurs at pumps, while 42% occurs in pipes (Figure 5.4). In reality, however, dissipation is even higher since the model is skeletonized and manufacturer standard pump curves are used.
When gravity flow increases, that is from tanks, rather than from reservoirs at the lakeshore, energy potential decreases. This is observed in the winter day scenario, when tanks are supplying more energy than in the summer day. Energy potential at the junctions varies, yet is not similar to the fluctuations in demand, nor energy delivered. Instead, it depends on pressure variations and how areas with distinct elevations consume water differently.

In both scenarios, the majority of energy delivered is for imminent use (80%) rather than storage (Figure 5.5). As could be expected, energy delivered to junctions, varies similarly to demand yet less intensely, since average pressure and velocity heads in the system tend to change inversely with demand, as displayed in Figure 5.6. Pressures peak at nighttime, when demands are lowest and dissipation is reduced. Energy supplied, however, remains fairly constant. This causes higher leakage rates, which could be decreased through pressure management with control valves, more efficient pump operation, or installation of variable speed pumps. The latter option, however, can increase costs in certain cases, such as dead end pressure zones or if flow is very low at times (Walski, 2011).

![Figure 5.5](image)

Figure 5.5: Total energy delivered per hour to tanks and junctions, during the summer (a) and winter (b) scenarios.
The daily energy costs and greenhouse gas emissions of the given winter scenario are CD$47,000 and 116 tCO₂ respectively. In the summer scenario, increased demands lead to greater energy costs, CD$60,000. Emissions, however, are unexpectedly lower, 107 tCO₂, because less energy from coal and natural gas sources is used. Overall, energy use for water pumping represents around 10% of all energy used and 8% of greenhouse gases emitted by city facilities in Toronto (City of Toronto, 2014).

Energy costs, and increasingly GHG emissions, are important factors in planning energy use. These are not necessarily opposing objectives. Electricity tariffs are generally highest during peak hours, and in Ontario, so are GHG emission factors (Figure 5.7 and Figure 5.8). While energy generated from renewable sources remains fairly constant throughout the day, fossil fuels meet the peak demands. If reducing costs is the primary objective, as is generally the case, extra water should be delivered to tanks at night so that the system can rely more gravity flow during the day. However for the given scenarios, modeling results show that energy supplied by pumps varies little compared to the fluctuation in electricity rates. A small reduction in pumping is observed during peak hours in the summer scenario, but in the winter scenario it even increases during the day (Figure 5.8).
The energy supplied by tanks oscillates throughout the day, especially in the winter scenario, which also causes energy dissipated in pipes to vary intensely. This occurs because the network is designed for larger, summer, flows. Therefore, during the winter pumps are cycled more often, as shown in Figure 5.8, and tanks often alternate between receiving and delivering flows.

Figure 5.7: Energy supplied by tanks and GHG emission factor per hour, during the summer (a) and winter (b) scenarios.

Figure 5.8: Energy supplied by pumps, and water rate per hour, during the summer (a) and winter (b) scenarios.

5.3.1.2 Modified summer scenario

In order for energy supplied by pumps to increase at night and for tanks to supply more of the peak demand, there must be sufficient pumping and storage capacity. Energy delivered to tanks would then vary inversely with demand. In the summer scenario, Figure 5.9, this effect is
observed at the beginning of the day, but as demand increases in the evening, more energy is delivered to tanks. In the winter scenario, despite the fluctuations, a trend can be seen as energy delivered to tanks increases as demands decrease.

![Graph showing energy delivered to tanks and demand delivered to junctions during summer and winter scenarios.](image)

Figure 5.9: Demand delivered to junctions and energy delivered to tanks per hour, during the summer (a) and winter (b) scenarios.

Based on the given model scenarios, tank capacity is not the primary constraint to decreasing energy supplied by pumps during peak electricity hours. Almost half of the pumps are kept on during the whole day in these scenarios, despite available tank capacity, high electricity costs, and slightly high pressures in the system. Usual Toronto Water practice is to reduce pumping at peak times. Additional controls might need to be added to the model so that results better approximate operator practices.

In order to assess potential improvements, a modified version of the summer scenario was run. In it, 20% of the open pumps were closed between 11 a.m. and 4 p.m. Energy supplied by pumps consequently decreases during this period by 5%, as shown in Figure 5.10a, but tanks provide pressure equalization and daily energy delivered to the junctions is only reduced 1%, (Figure 5.10b). Electricity costs and GHG emissions are reduced by 6%. Over an extended period, however, even if tanks were maintained at lower levels this temporary reduction in pumping would be offset by a subsequent increase in order to refill tanks. Therefore, significant changes could only be made to costs and emissions by altering pump scheduling. Even a 5% reduction to
pumping electricity costs and greenhouse gas emissions could save approximately CD$ 0.9 M and 750 tCO₂ in one year (City of Toronto, 2014).

Figure 5.10: Energy supplied by pumps (a) and delivered to junctions (b) during the summer scenario for the original and modified pump controls.

Although the metrics can help uncover various types of modifications to the system, herein only one alteration to one scenario was modeled. This is meant to illustrate the usefulness of the metrics and how slight changes to the system can promote important benefits. Besides adjusting pumping hours, other alterations might include dividing pressure districts, reducing maximum pressures, cleaning and relining pipes, installing pipes, adjusting storage controls, as well as adding storage or pumping to the system. In order to support these modifications and assess their long-term effects, more scenarios would also need to be analyzed.

5.3.1.3 Mapping the metrics

By calculating the energy metrics by network component, different from previous methods, they allow for mapping. This novel approach facilitates the identification of specific target areas for improvement, be it through infrastructure renewal, pressure management, or conservation. Figure 5.11 to Figure 5.13 map the energy metrics of the system during peak demand in the summer scenario. Higher energy dissipation rates in mains, shown in darker grey in Figure 5.11, indicate an increased probability of failure. These pipes, which according to Toronto Water have indeed experienced more bursts, are located mostly on the waterfront and downtown (central south),
where water leaves the treatment plants. These should, thus, be further assessed and more closely maintained. Pumps that dissipate large amounts of energy are also key objects for refurbishment.

During this period, pumps provide most of energy supplied (Figure 5.12), while tanks predominantly receive water (Figure 5.13). Highest energy delivery rates to junctions are observed downtown and in the northwest, prompting inquiries into pressure management and perhaps conservation. However, further away from the downtown core and the waterfront, there are fewer branches and delivery points in the system. Therefore, energy delivered could seem artificially high because of the larger populations supplied.

![Map of energy dissipated in the Toronto water distribution network during peak demand (8 p.m.) on maximum demand day.](image)
Figure 5.12: Map of energy supplied in the Toronto water distribution network during peak demand (8 p.m.) on maximum demand day.

Figure 5.13: Map of energy delivered in the Toronto water distribution network during peak demand (8 p.m.) on maximum demand day.
Improvements to the system can also be prioritized according to energy delivered, as areas that receive more energy generate greater costs. While revenue is generally a function of demand (water rates in Toronto are based on volumetric consumption) expenses are a more complex function of multiple variables, creating the potential for ineffective cost allocation. The energy metrics can be applied in better understanding these expenses. The Electric Power Research Institute (2002) discusses some of the factors that can influence unit electricity consumption, such as system age, restrictions, standards, economies of scale, and equipment replacement. However, the extent of their impact to consumption depends on the system itself. Modeling the network with hydraulic models can also provide a greater level of detail to decision-making.

Given the results from the energy metrics, identified target areas, and potential solutions, alternatives can be simulated and compared to the base scenario to confirm they indeed solve the issue. Future studies can use these metrics to analyze different networks, scenarios, and alternatives for improvement. The metrics can also be complemented with more detailed data, such as break and leakage rates, in order to further study correlations.

5.3.1.4 Extensions of the study

The metrics proposed herein have been presented to the Toronto Water staff. Comments and questions from these meetings inspired many of the previous discussions of the metrics and their applications. The metrics and the lens of sustainability they add to system analysis invoke inquiries over concepts that were taken for granted, such as operational paradigms, maintenance strategies, rate structures, and standards. If expense reduction is the goal, or, more holistically, sustainability, a decrease in energy consumption is central, as well as the use of more renewable energy sources. Both objectives are achieved through the reduction of pressure and flow, perhaps with refurbished pumps, new pipes, more conservation initiatives and revised pressure requirements.

The present research and findings inspired further applications and studies. The energy costs and inefficiencies faced by the Toronto network not only motivated investigations into pressure management, but also a comparative study of international fire flow and residual pressure standards. These differ by country, as paradigms and practices regarding failure mitigation vary.
North American standards are among the most restrictive even though system safety is maintained with lower flows and pressures in other regions.

While high pressures in the northern part of the network could be addressed through pressure management, the simultaneous occurrence of high and low pressures in the downtown pressure district prompted further research into the motivating factors and effects of dividing pressure districts. Whether by installing pressure reducing valves, decreasing pumping, or dividing pressure districts, altering pressures, even within current standards, can affect customer satisfaction, demands, and utility revenue. Accordingly, the potential revenue impacts of pressure management were investigated as well as example cases of water rate structures that account for different delivery pressures.

5.4 Conclusions

The present chapter proposes several integrated energy metrics and applies them to a case study of the Toronto water distribution system. These assess more than electricity consumption. Energy supplied is an indicator of operational costs as well as greenhouse gas emissions, and can thus be used to support a business case for reducing network energy use. Energy lost represents system leakage and the need for pressure management as well as increased maintenance, while energy dissipated also reveals the need for demand management. Energy delivered shows how much energy actually reaches the consumer and, accordingly, motivates improvements to zoning, design standards, as well as reducing pressures and demands.

Calculating the metrics by component disaggregates water distribution systems so that they are not analyzed as a simple black box with inputs and outputs, and allows for the identification of areas or specific system components, where changes are most beneficial. This novel approach enables the mapping of energy metrics, providing a geographical snapshot of the system.

In the Toronto case study, the amount of energy dissipated (37%), used in overcoming pipe and valve friction, as well as pump inefficiencies, was found to be similar to energy potential (35%),
used in overcoming elevation differences. This is in part due to the size of the network and the low elevation of the reservoirs. Only 28% of energy supplied is delivered to junctions in the form of pressure and flow. Consequently, users receive even less, and this inefficiency creates an important environmental and economic impact. In the modeled scenarios, pumping is not significantly adjusted to take advantage of off peak electricity rates or lower GHG emission factors, a practice which Toronto Water seeks to follow. This prompted the development of a modified scenario, in which peak pumping was reduced by 20%, yet energy delivered was not greatly affected. This was shown to yield a reduction of 6% to electricity costs and GHG emissions, revealing the potential benefits of this practice. Nevertheless, an extended simulation would be needed to assess if safe tank levels can still be maintained.

Mapping energy dissipated revealed key mains for retrofitting in the downtown. Energy delivered is also highest in this area, which means it could benefit from pressure management and conservation. While the metrics have shown to be useful indicators of energy efficiency, infrastructure performance, and costs, as verified by Toronto Water, additional data is required to support decision-making. In future studies, as in the extended research being completed in Toronto, the analysis of different scenarios and network configurations can inform the revision of design standards, operational requirements and maintenance scheduling. In addition, by systematically applying this methodology to a set of different systems, results can be compared and generalized between municipalities and benchmarks defined.
6 Performance Metrics

The energy metrics proposed in chapter 5 are indicators of system capacity, efficiency, GHG emissions, and specific operational and capital costs. The current chapter applies these in expanding the analysis of the network, and assessing its performance under different operation conditions. Because these metrics are derived from the variation of energy metrics over different normal and emergency conditions, they can also be modeled with EPANET and can easily be applied by utilities. Previous studies have equated water distribution network performance to the ability to deliver sufficient pressure and flow. The present chapter argues that this performance also depends on the efficiency of delivering these requirements.

The present chapter is based on the manuscript entitled “Performance Index for Water Distribution Networks Under Multiple Loading Conditions” by Rebecca Dziedzic and Bryan Karney, submitted to the Journal of Water Resources Planning and Management. It addresses the issue of assessing the performance of complex systems, and how it depends on network design, operations, and maintenance.

6.1 Performance of water distribution networks and other complex systems

The performance of water distribution networks is multi-objective and dependent upon complex interactions between infrastructure components as well as with external conditions. This can be compared ecosystems, which must balance population requirements against outside pressures. Indeed, previous authors have found that ecosystems function according to principles that increase network sustainability, such as resilience and reliability (Biomimicry 3.8 Institute, 2011; Ho and Ulanowicz, 2005; Katifori et al., 2010).

The classic 1973 study by Holling argues that evolution finds a balance between two related system characteristics, namely resilience and stability, with resilience being a term coined for
ecosystems to indicate a system’s ability to absorb changes of state variables. Thus, resilience is related to the concept of persistence, while stability indicates the ability of these systems to return to an equilibrium state after a temporary disturbance. Therefore, a stable system would not fluctuate greatly, and a resilient system might undergo significant fluctuations. Klein et al. (2003) note that despite the continuous debate since the seminal work by Holling (1973), a consensus on how to operationalize this concept has not been reached. For instance, Timmerman (1981) links resilience to vulnerability and defines the first as the measure of a system’s capacity to absorb and recover from a hazardous event. Pimm (1984) connects resilience with stability: resilience is the speed with which a system returns to its original state after a temporary disturbance. This definition concerns engineering resilience, which considers ecological systems to exist close to a single stable steady state (Holling, 1996). Ecological resilience, on the other hand, emphasizes instabilities, which can lead the system to still function but in another state.

Fiering (1982a) introduces several indices to measure the resilience of water resource systems. These are related to various system attributes including the probability of the system being in an acceptable state, the probability of failure, the costs of being in each state, as well as expected time to change states. Each of these represent different properties of the system, all of which favourably indicate a system’s performance, and all are highly correlated (Fiering 1982b).

Hashimoto et al. (1982) instead developed a single concept for evaluating water supply system resilience, and two additional concepts, vulnerability, and reliability to assess system performance. In Hashimoto, resilience is the probability of recovery from failure within a specified time interval. As applied to water supply, this is calculated as the probability of quickly meeting demand after an instance of insufficient supply (Hashimoto et al., 1982; Moy et al., 1986; Solis et al., 2011). Reliability is the probability of water supply meeting demand during the period of the simulation (Klemeš et al. 1981; Hashimoto et al., 1982; Moy et al., 1986; McMahon, 2006; Solis et al., 2011). Vulnerability, introduces another consideration, being a measure of the significance (or consequences) of failure (Hashimoto et al., 1982). This is often calculated as direct surrogate of costs, such as the average demand deficit during failure events.
(Loucks and van Beek, 2005; Solis et al., 2011) or the largest deficit during the period of operation (Moy et al., 1986).

For the analysis of water distribution networks, resilience has largely acquired another meaning, more related in earlier work to the concept of robustness. Todini (2000) defined water distribution resilience as the ability of the network to provide more power than required at each noted in order to have a sufficient surplus to be dissipated internally in case of failure. This resilience index (6.1) is applied as a surrogate measure of network reliability.

$$RI = \frac{\sum_{j=1}^{n} q_j (h_{a_j} - h_{r_j})}{\left(\sum_{r=1}^{R} Q_r H_r + \sum_{b=1}^{B} P_b\right) - \sum_{j=1}^{n} q_j h_{r_j}}$$

where $n$ is the number of demand nodes, $q_j$ the demand at node $j$, $h_{a_j}$ head available at node $j$, $h_{r_j}$ minimum head required to meet constraints at node $j$; $R$ the number of reservoirs, $Q_r$ the flow being supplied to the system by reservoir $r$, $H_r$ the head at reservoir $r$, $P_b$ the power introduced in the system by pump $b$ into the system.

Todini’s resilience index has been widely adapted and applied to water distribution system studies (Todini, 2000; Prasad and Park, 2004; Jayaram and Srinivasam, 2008; Baños, 2011; Atkinson, 2014; di Nardo, 2014). Prasad and Park (2004) combine the resilience index with a diameter uniformity coefficient (6.2) in order to better represent the reliability of loops. The resulting network resilience index $NRJ$ is given in (6.3).
\[ c_j = \frac{\sum_{i=1}^{n_p} D_j}{np \cdot \max(D_j)} \] (6.2)

\[ NRI = \frac{\sum_{j=1}^{n} c_j q_j (h_a_j - h_r_j)}{\left( \sum_{r=1}^{n} Q_r H_r + \sum_{b=1}^{n} P_b \right) - \sum_{j=1}^{n} q_j h_r_j} \] (6.3)

where \( np \) is the number of pipes connected to node \( j \), and \( D \) the diameter of these pipes.

Prasad and Park (2004) argue that reliable are achieved if the pipes connected to a node are not widely varying in diameter. However, the proposed uniformity coefficient does not fully represent the advantage of loops; indeed the coefficient is equal to 1 if all pipes connected to a node have the same diameter even if there is only connection. If a pipe were to burst, however, a one-pipe-node would obviously be less reliable.

Jayaram and Srinivasan (2008) moreover show that Todini’s resilience index does not adequately represent the reliability of networks with multiple reservoirs. Because the power supplied by reservoirs depends on pipe diameter and roughness, a network with a large surplus power at the demand might also have a large input power, undesirably decreasing the resilience index. Thus, Jayaram and Srinivasan (2008) propose a modified resilience index, \( MRI \), as given in (6.4).

\[ MRI = \frac{\sum_{j=1}^{n} q_j (h_a_j - h_r_j)}{\sum_{j=1}^{n} q_j h_r_j} \] (6.4)

Baños et al. (2011) compare these three resilience indices through a cost versus reliability study. The modified indices are found to be only marginal improvements upon the original index by Todini (2000). Baños et al. (2011) also note that none of these indices consider the issue of over-
demand is applied, and thus do not accurately determine the capability of the network to deliver demand under uncertainty.

While these indices do not fully consider the connectivity of a network, and cannot identify critical areas in the system, Yazdani et al. (2011) focus on non-hydraulic statistical and structural metrics for assessing water distribution network resilience. The connectivity pattern between nodes and links is used to calculate reliability, efficiency and robustness of the networks. Tanyimboh and Templeman (1999) also evaluate network performance according to non-hydraulic metrics. The authors introduce the concept of entropy in water networks, entropy being defined as the probability of a node receiving demands given the availability of adequate alternate flow paths.

Creaco et al. (2014) compare the resilience and entropy metrics as indirect measures of network reliability. The demand satisfaction rate is assumed to be a natural performance indicator, and a direct measure of reliability; it is calculated as the ratio of demand delivered to demand required, based on a pressure driven simulation. The maximum reliability is reached by just meeting the minimum pressure required to satisfy demands. Pressures above this level do not alter the assessment of reliability of the network. Given this definition, the resilience indices showed a much stronger positive correlation with network reliability. Zhuang et al. (2013) and Di Nardo et al. (2014), in fact, apply the demand satisfaction rate directly to support the assessment of water distribution networks.

Even the demand satisfaction rate, although dependent upon pressure as well, clearly does not fully represent the performance of water networks. Delivering pressures above the minimum requirement to meet full demands does not affect this rate, but does alter both costs and how the network operates. The resilience metrics account for all pressures, but are partial to higher network pressures, which despite inducing the supply of surplus power might well lead to higher leakage and burst rates. The present paper argues that the performance of the network should depend not only on the ability to deliver adequate flows and pressures, but also on its efficiency in doing so.
As argued when introducing previous resilience indices, power is an attractive measure in assessing networks since it is proportional to pressure and flow, the main products of the system. Cabrera et al. (2010) propose energy indicators to evaluate the efficiency of networks, defined according to ratios between energy supplied, energy lost, and useful energy or minimum required useful energy. These are calculated at a system level for a long-term period in order to represent its energy balance. Chapter 5 proposes water distribution system energy metrics that are computed for each component at each time step. This facilitates both the identification of areas for improvement and the comparison of operational efficiency in different scenarios.

The current study proposes efficiency-based performance metrics for evaluating and comparing water distribution networks. These metrics accommodate varying loads and multiple network components in order to represent network connectivity, capacity to deliver demand under uncertainty, and ability to recover after emergencies. The metrics are applied to two example networks and variations of these, enabling and provisionally validating their use in as network assessment tools.

6.2 Performance Index

Four metrics are herein defined for evaluating water network performance: reliability, resilience, vulnerability, and connectivity. The first three are conceptually based on definitions used in water basin management, as described in the previous section (Klemes et al. 1981; Hashimoto et al., 1982; Moy et al., 1986; Loucks and van Beek, 2005; McMahon, 2006; Solis et al., 2011).

Because the performance of water networks depends on the efficient delivery of sufficient demand and pressure, energy efficiency is applied instead of demand to compute the metrics. Furthermore, unlike in water basin studies where a minimum demand is established, or the network resilience indices where a minimum pressure is determined, a minimum efficiency constraint has not been established. Accordingly, the proposed metrics do not evaluate the probability of the network meeting a minimum efficiency, but rather the efficiency of the
network under various conditions. Failure events, in which demand and pressure requirements are not met, are also characterized by a reduction in energy efficiency. Nevertheless, to evaluate a wide range of conditions, the metrics naturally an extended period analysis.

Energy efficiency, as represented by (6.5) and (6.6), is herein defined as the ratio between total energy delivered $E_{\text{delivered}}$ and energy supplied $E_{\text{supplied}}$. The first represents energy available at nodes, through the demand and head delivered, in the various scenarios. The second is the sum of energy supplied at tanks, reservoirs, and pumps, through gravity or pumped flow. Unlike previous resilience indices, the total energy consumed by the pumps, rather than the energy introduced to the network after the initial dissipation at the pumps, is considered. This integrates the efficiency of the pumps in the analysis of the network.

$$e = \frac{E_{\text{delivered}}}{E_{\text{supplied}}}$$  \hspace{1cm} (6.5)

$$e = \frac{\sum_{j=1}^{N} q_{j}h_{a_{j}}}{\sum_{r=1}^{R} Q_{r}H_{r} + \sum_{b=1}^{B} P_{b}^{*}}$$  \hspace{1cm} (6.6)

Reliability $P_{\text{rel}}$, related to the system’s performance under all potential conditions, is defined as the average energy efficiency over all scenarios, as given by (6.7), where $h$ is the number of simulation hours in one scenario, and $s$ the number of scenarios. These scenarios should represent the normal and emergency conditions of the network. In this way a long term analysis of the network is progressively accomplished. In the present study, for an initial evaluation of the metrics, only three scenarios are run with the example networks, representing scenarios with normal flow, fire flow, and pipe burst. These are important design scenarios and emergency events for water distribution systems in general. Future studies can easily be extended to include other cases such as pump breakdown and valve failure, or even a stochastic analysis of the life cycle of the network.
Vulnerability $P_{\text{val}}$ is used here to represent a measure of the severity of failure. It is the minimum efficiency reached by the system during emergency events or normal operation (6.8). Together with the other metrics it is indicative of the range of system efficiency.

$$P_{\text{val}} = \min\left(e_{t,i}\right) \tag{6.8}$$

Similar to reliability, resilience $P_{\text{res}}$ (6.9) is calculated as the average efficiency, but after a failure event. It implicitly reflects the system’s capacity to adapt to change. This post emergency period $h^*$ should be long enough to represent recovery. For the example networks modeled, a period of four hours was used.

$$P_{\text{res}} = \sum_{i=1}^{s^*} \sum_{h^*}^{} \frac{e_{t,i,s^*}}{s^* h^*} \tag{6.9}$$

These energy-based metrics describe system performance under different conditions. However, because total pipe failure was not modeled, but only burst induced leakage, the measures do not fully represent the advantage of loops creating alternate flow paths. Yazdani et al. (2011) used statistical measurements of water distribution networks to analyze robustness and redundancy. They are based on the structural patterns and building blocks of the network. Herein, this concept was extended; and a structural metric was related to demands. Network connectivity was defined as the minimum percentage of demand $Q$ delivered given a pipe $p$ break (6.10).

$$P_{\text{con}} = \min\left(\frac{Q_{\text{del},p}}{Q_{\text{req},p}}\right) \tag{6.10}$$

The connectivity of the network could be calculated by hydraulically modelling all of the potential bursts, yet a structural surrogate measure is herein proposed to estimate connectivity.
The connectivity vector, given in (6.11), indicates if nodes are connected to a source of water. The network is represented as an adjacency matrix, $A$, of order $n \times n$, where $n$ is the number of nodes. The elements of the matrix represent the network connections. As usual, lines and columns indicate specific nodes with values of 1 indicating that a pipe directly connects the respective nodes, and 0 otherwise. The location of the sources is represented in a vector, $c_0$, where elements are either 1 if the node is a source or 0 if not. The elements of the resulting connectivity vector, $c$, are 0 if the particular node is not connected to any source of water, and different from 0 if it is.

$$c = \sum_{j=1}^{n} c_0 A^j$$

For the purposes of this study, the demand-based connectivity, (6.10), was thus estimated assuming that a network connection between a source of water and a node would suffice for water to be delivered. In order to evaluate these collectively, an aggregate performance index is proposed. As shown in (6.12), this aggregate measure is taken as the geometric average of the performance metrics ($P_m$): reliability, resilience, vulnerability, and connectivity. Because these are ratios of either “energy delivered to supplied” or “demand delivered to required”, they all range between 0 and 1. The upper limit indicates the best situation. Other properties of this type of index are attractive: (1) if one of the metrics is zero, the index will be zero; (2) if the metrics are all equal, so is the overall measure; (3) there is an implicit weighting, through which the “worst” metrics are given more importance; and (4) each metric is considered essential and irreplaceable. In accordance with the second property, results from a geometric average are similar to those from an arithmetic average if efficiencies are consistent. However, for systems with a wider range of performance, because the worst metrics are given more importance, the geometric average represents this inconsistency better.
In order to assess the performance and usefulness of the metrics, two example networks are assessed, with each having a range of pipe redundancy increasing strategies, as well as pumping and storage scenarios. Increasing network redundancy, whether through adding pipes or other components, is a recognized strategy for increasing network performance, especially resilience (Awumah et al., 1990; Goulter, 2004; Walski, 2004; National Research Council, 2006; U.S. Department of the Interior Bureau of Reclamation, 2006; Yazdani et al., 2011). The proposed metrics were also compared to the resilience indices developed by Todini (2000), Prasad and Park (2004), and Jayaram and Srinivasam (2008), as well as the average pressure of the network.

The two example networks modeled are based on examples distributed with EPANET (2000). They were selected because both are not only well known but have at least one reservoir, tank, and pump, as well as hourly varying demands. This allows for the analysis of storage and multiple loading conditions not evaluated by other authors (Todini, 2000; Baños, 2011; Atkinson, 2014). The demand patterns were altered to better represent urban demand, with two peaks, in the morning and the evening (Blokker et al., 2010). Demand, however, was set to fluctuate more than would be expected during normal operations, varying between minimum (0 h), average (3 h), maximum (6 h), and peak demand (17 h) throughout the day, shown in Figure 6.1. Peaking coefficients were based on recommendations from Municipal Engineers Association (1977) and Ysusi (1999). This not only enables the analysis of different extreme scenarios, but also of system response to wide variations in demand. Further network modifications were made in order to maintain normal operations within standard pressure ranges. Pressure ranges were verified for the original looped configurations of the networks. However, in other configurations,
pressures were found to be below operational standards, leading to greater vulnerability $P_{val}$. Network characteristics are described in the following sections.

With the objective of assessing the systems as well as the applicability and sensitivity of the performance metrics, the aforementioned strategies were applied to the example networks. For each example network, three variations were modeled: the original design (with loops), the network with fewer loops, and the network with fewer loops yet larger pipe diameters. In the last case all pipe diameters were increased by 100 mm. Schematic representations of the looped networks are shown in Figure 6.2 and Figure 6.4. Characteristics of the pipes and whether or not they are included in the second scenario are presented in Table 6.2 and Table 6.5.

![Figure 6.1: Peaking coefficients for Networks 1 and 2.](image)

Furthermore, for each of these configurations, three 1-day scenarios were analyzed: normal demand pattern (Figure 6.1), fire flow during maximum demand, and pipe burst during peak demand. The last scenario, unlike the former, is usually not considered in the design of water distribution systems even though it constitutes a significant emergency caused by system failure. Fire flow was set at a critical (low pressure) point in each network, and water loss due to a pipe burst was located in an area with high energy dissipation, which would possibly be more prone to cracking or failure.
The additional demands due to fire and leakage, each with a duration of 2 hours, were assigned to dummy nodes, connected to the network by short pipes with insignificant head loss. The fire flow was determined based on the demands in the system and the ISO (2008) recommendations for residential dwellings. In Network 1, the fire flow is $63 \text{ L.s}^{-1}$, and in Network 2, $126 \text{ L.s}^{-1}$. Lambert et al. (2000) compared seven North American water distribution systems. Their leakage rates represented between 15 and 33% of total system input volume. In the present models, the leakage in the pipe burst scenario was set to 20% of total demand. Although this is clearly a significant flow at a single node, it is less than many consistent leakage rates, and allows for the assessment of critical leakage on network performance. Leaks were defined as emitters in EPANET, with a pressure exponent of 1, as suggested by Lambert (2000). This resulted in a discharge coefficient of 0.7 for Network 1 and 2.9 for Network 2.

### 6.3.1 Example Network 1

Network 1 is a simple 3 loop-network, shown in Figure 6.2. It has one reservoir and one tank, both at higher elevations than the remaining nodes. The initial level of the tank is 36 m, while the minimum and maximum level are 31 m and 46 m, respectively. Although gravity flow does play a role in supplying flow, pumping is still required. The pump curve is defined by one head vs. flow coordinate, 76.2 m for 94.6 L.s$^{-1}$.

Three network configurations were modelled: the original (looped) system, the same system with fewer loops, and with increased diameters. The basic node characteristics are the same for all three and are given in Table 6.1. Pipe characteristics of the looped network are listed in Table 6.2. In the second configuration, three pipes were removed, indicated by an asterisk in Table 6.2, and all other characteristics were maintained. In the third configuration, the same pipes are removed yet all other diameters are increased by 100 mm.

The average pumping energy varies minimally between the three modeled configurations of Network 1, original (looped), fewer loops, and increased diameters, as shown in Table 6.3. Therefore, operational energy costs are stable despite structural differences. The energy dissipated however, varies significantly. The configuration with fewer loops consistently
presents lower pressures and energy efficiency. Consumers would be receiving an inferior service in this case, and utilities would be spending more money on overcoming friction. Risks associated with pipe breaks or low pressures would also be higher.

Table 6.1: Elevation and demand values for Network 1 nodes.

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Elev (m)</th>
<th>Q (L.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res</td>
<td>243.8</td>
<td></td>
</tr>
<tr>
<td>Tank</td>
<td>259.1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>216.4</td>
<td>0.0</td>
</tr>
<tr>
<td>11</td>
<td>216.4</td>
<td>9.5</td>
</tr>
<tr>
<td>12</td>
<td>213.4</td>
<td>9.5</td>
</tr>
<tr>
<td>13</td>
<td>211.8</td>
<td>6.3</td>
</tr>
<tr>
<td>21</td>
<td>213.4</td>
<td>9.5</td>
</tr>
<tr>
<td>22</td>
<td>211.8</td>
<td>12.6</td>
</tr>
<tr>
<td>23</td>
<td>210.3</td>
<td>9.5</td>
</tr>
<tr>
<td>31</td>
<td>213.4</td>
<td>6.3</td>
</tr>
<tr>
<td>32</td>
<td>21.6</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Figure 6.2: Schematic representation of Network 1 with node IDs. Table 6.2: Length, diameter, and roughness coefficient values for Network 1 pipes.
**Table 6.3**: Average energy metrics of the alternative configurations of Network 1, L – fewer loops, D – larger diameters.

<table>
<thead>
<tr>
<th>Pipe ID</th>
<th>Start Node</th>
<th>End Node</th>
<th>L (m)</th>
<th>D (mm)</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>11</td>
<td>3209.5</td>
<td>457.2</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>12</td>
<td>1609.3</td>
<td>355.6</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>13</td>
<td>1609.3</td>
<td>254.0</td>
<td>100</td>
</tr>
<tr>
<td>21*</td>
<td>21</td>
<td>22</td>
<td>1609.3</td>
<td>254.0</td>
<td>100</td>
</tr>
<tr>
<td>22</td>
<td>22</td>
<td>23</td>
<td>1609.3</td>
<td>304.8</td>
<td>100</td>
</tr>
<tr>
<td>31</td>
<td>31</td>
<td>32</td>
<td>1609.3</td>
<td>152.4</td>
<td>100</td>
</tr>
<tr>
<td>110</td>
<td>Tank</td>
<td>12</td>
<td>61.0</td>
<td>457.2</td>
<td>100</td>
</tr>
<tr>
<td>111</td>
<td>11</td>
<td>21</td>
<td>1609.3</td>
<td>254.0</td>
<td>100</td>
</tr>
<tr>
<td>112*</td>
<td>12</td>
<td>22</td>
<td>1609.3</td>
<td>304.8</td>
<td>100</td>
</tr>
<tr>
<td>113</td>
<td>13</td>
<td>23</td>
<td>1609.3</td>
<td>203.2</td>
<td>100</td>
</tr>
<tr>
<td>121</td>
<td>21</td>
<td>31</td>
<td>1609.3</td>
<td>203.2</td>
<td>100</td>
</tr>
<tr>
<td>122*</td>
<td>22</td>
<td>32</td>
<td>1609.3</td>
<td>152.4</td>
<td>100</td>
</tr>
</tbody>
</table>

* Pipes not included in the configuration with fewer loops

The daily energy efficiency profiles of the alternative configurations of Network 1 are shown in Figure 6.3. The percentage of energy delivered, equivalent to $e$, in the original looped configuration of Network 1 varies between 80 and 84%. The additional demands during peak hours as well as during fire events increase system efficiency (Figure 6.3a). Despite the increased energy dissipation in the pipes due to larger flows, tanks supply more water during this period. This allows pumps to operate at the same level, at similar dissipation rates as during normal operations, momentarily increasing efficiency. Obviously this efficiency cannot be sustained but shows how storage can be used to maintain the reliability of the system. This is also true in the configuration with increased diameters (Figure 6.3c), but not in the case with fewer loops (Figure 6.3b). In the latter, the additional flow during fire events and peak hours causes excessive pipe dissipation, reducing energy efficiency. In all three cases, then the burst occurs during peak flow, the energy lost through leakage causes efficiency to plummet.
Figure 6.3: Energy efficiency profile over 24-hour simulation for Network 1 (a) original network, (b) fewer loops, (c) larger diameters.
Table 6.4: Proposed performance metrics, resilience index (Todini, 2000), network resilience index (Prasad and Park, 2004), modified resilience index (Jayaram and Srinivasam, 2008), and average pressure of the alternative configurations of Network 1, L – fewer loops, D – larger diameters.

<table>
<thead>
<tr>
<th>Network</th>
<th>Rel</th>
<th>Vul</th>
<th>Res</th>
<th>Con</th>
<th>PI</th>
<th>RI</th>
<th>NRI</th>
<th>MRI</th>
<th>Avg P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net 1</td>
<td>0.84</td>
<td>0.80</td>
<td>0.83</td>
<td>1.00</td>
<td>0.86</td>
<td>0.99</td>
<td>0.80</td>
<td>1.15</td>
<td>83.94</td>
</tr>
<tr>
<td>Net 1 L</td>
<td>0.77</td>
<td>0.54</td>
<td>0.79</td>
<td>0.59</td>
<td>0.66</td>
<td>0.87</td>
<td>0.76</td>
<td>0.97</td>
<td>78.60</td>
</tr>
<tr>
<td>Net 1 L, D</td>
<td>0.83</td>
<td>0.71</td>
<td>0.82</td>
<td>0.59</td>
<td>0.73</td>
<td>0.97</td>
<td>0.87</td>
<td>1.12</td>
<td>83.14</td>
</tr>
</tbody>
</table>

These differences are clear in the performance metrics shown in Table 6.4. While reliability and resilience are similar for the configurations with greater redundancy, they are lower in the configuration with fewer loops. The greater connectivity and lower vulnerability in the looped network lead to a higher performance index, setting it apart from the configuration with larger diameters.

The proposed performance index follows the same trend as the resilience index by Todini (2000) and the modified resilience index by Jayaram and Srinivasam (2008). All indicate that the looped configuration has the best performance. Nevertheless, the difference between the looped and the larger diameter configuration is small according to the resilience indices. Because these are proportional to the power surplus they vary similarly to the average pressure of the networks. The inclusion of vulnerability and connectivity into the proposed performance index helps to distinguish the real performance differences of the networks.

The index defined by Prasad and Park (2004) is the only metric that is more partial to the configuration with no loops and larger diameters. Removing pipes or increasing diameters has a greater effect on node uniformity in smaller networks, such as the given example. Thus, an advantage is given to branched networks with more nodes reached only by a single pipe.

6.3.2 Example Network 2

Network 2 is more complex and better represents many systems. It has two reservoirs, three tanks, and two pumps, shown in Figure 6.4. In this case, nine configurations were modelled in order to assess modifications to storage and pumping, as well pipe redundancy. Three storage and pumping configurations were evaluated: the original, a scenario with reduced storage, and
one with reduced storage and pumping. The head versus flow coordinates of the pump curves and tank levels of the original configuration are presented in Table 6.5 and Table 6.6, respectively. In the second case, the maximum levels of the tanks were reduced to equal their initial levels. In the third case, in addition to reducing storage, head imparted at pump 2 was decreased by half.

Three pipe configurations were modelled for each case: original (looped), fewer loops, and increased diameters. The common node characteristics are the same for all three systems and are given in Figure 6.4. Pipe characteristics of the looped network are listed in Table 6.8. In the second configuration, three pipes were removed, indicated by an asterisk in Table 6.8, and all other characteristics were maintained. In the third configuration, the same pipes are removed yet all other pipe diameters are increased by 100 mm.

Table 6.5: Pump curve coordinates, flow and head, for Network 2.

<table>
<thead>
<tr>
<th>Pump 1</th>
<th>Pump 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (L.s⁻¹)</td>
<td>H (m)</td>
</tr>
<tr>
<td>0</td>
<td>63</td>
</tr>
<tr>
<td>126</td>
<td>56</td>
</tr>
<tr>
<td>252</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 6.6: Tank levels for Network 2.

<table>
<thead>
<tr>
<th>Tank ID</th>
<th>Initial Level</th>
<th>Minimum Level</th>
<th>Maximum Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>0.03</td>
<td>9.8</td>
</tr>
<tr>
<td>2</td>
<td>7.2</td>
<td>2</td>
<td>12.3</td>
</tr>
<tr>
<td>3</td>
<td>8.8</td>
<td>1.2</td>
<td>10.8</td>
</tr>
</tbody>
</table>
Figure 6.4: Schematic representation of Network 2 with node IDs.
### Table 6.7: Elevation and demand values for Network 2 nodes.

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Elev (m)</th>
<th>Q (L.s⁻¹)</th>
<th>Node ID</th>
<th>Elev (m)</th>
<th>Q (L.s⁻¹)</th>
<th>Node ID</th>
<th>Elev (m)</th>
<th>Q (L.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res1</td>
<td>50.9</td>
<td></td>
<td>143</td>
<td>-1.4</td>
<td>0.4</td>
<td>206</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Res2</td>
<td>67.1</td>
<td></td>
<td>145</td>
<td>0.3</td>
<td>1.7</td>
<td>207</td>
<td>2.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Tank1</td>
<td>39.3</td>
<td></td>
<td>147</td>
<td>5.6</td>
<td>0.5</td>
<td>208</td>
<td>4.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Tank2</td>
<td>40.2</td>
<td></td>
<td>149</td>
<td>4.9</td>
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<td>13868</td>
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<td>155</td>
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<td>601</td>
<td>61</td>
<td>0</td>
<td>762</td>
<td>140</td>
</tr>
</tbody>
</table>

* Pipes not included in the configuration with fewer loops
Although energy supplied by pumps in the original Network 2 configuration (Table 6.9) is not much different from that in Network 1, energy dissipated is about four to five times higher in the former. This low efficiency is largely due to the high percentage of energy dissipated in the pipe leaving pump 2, which conveys most of the flow when reservoirs are supplying water. The original Network 2 experiences a wide variation in energy dissipated and consequently in energy efficiency $e$, which increases throughout the day from 45 to 70% (Figure 6.5a). These represent extremes of operation, with large flows in the pipes due to tank filling at the beginning of the simulation, and small flows at the end. The higher efficiency could, thus, not be sustained and this 24 hour period does not represent a full cycle of operation.

Table 6.9: Average energy metrics of the alternative configurations of Network 2, L – fewer loops, D – larger diameters, S – reduced storage, P – reduced pumping.

<table>
<thead>
<tr>
<th>Network</th>
<th>Pump $E_{\text{supplied}}$ (kWh)</th>
<th>$E_{\text{dissipated}} + E_{\text{lost}}$ (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net 2</td>
<td>96.0</td>
<td>135.1</td>
</tr>
<tr>
<td>Net 2 L</td>
<td>95.7</td>
<td>142.0</td>
</tr>
<tr>
<td>Net 2 L,D</td>
<td>77.3</td>
<td>99.6</td>
</tr>
<tr>
<td>Net 2 S</td>
<td>207.2</td>
<td>115.6</td>
</tr>
<tr>
<td>Net 2 S,L</td>
<td>208.1</td>
<td>125.1</td>
</tr>
<tr>
<td>Net 2 S,L,D</td>
<td>204.6</td>
<td>88.4</td>
</tr>
<tr>
<td>Net 2 S,P</td>
<td>135.4</td>
<td>96.6</td>
</tr>
<tr>
<td>Net 2 S,P,L</td>
<td>135.7</td>
<td>106.5</td>
</tr>
<tr>
<td>Net 2 S,P,L,D</td>
<td>135.0</td>
<td>70.5</td>
</tr>
</tbody>
</table>

During the initial hours of the original Network 2 simulation, both tanks are being filled at a rate that is more than seven times greater than the total demand at junctions. However, less than 10% of the water stored is used during peak flow. Therefore, the rate of tank filling is inconsistent with the rate of draining, generating unnecessarily high flows and head loss. The effects of oversizing tanks go beyond water quality if they are not operated adequately. Tanks are generally filled when electricity prices are lowest, at night, which coincides with low water demand. Nonetheless, the rate at which they are filled must be carefully considered as indicated by the low energy efficiency of Network 2. The principal purpose of tanks is to provide pressure equalization, allowing the system to operate closer to a steady state. If tank demand is unnecessarily high this is not achieved.
Figure 6.5: Energy efficiency profile over 24-hour simulation for Network 2 (a) original network, (b) reduced storage, (c) reduced storage and pumping.
Because of its high localized head loss in this case, the configuration with larger diameters produced the highest energy efficiency, as shown in Table 6.10. Accordingly, all of the performance metrics, except for connectivity are also higher in this configuration. Because connectivity is only marginally reduced by decreasing the number of loops, this is the best performing configuration according to the proposed performance index.

Table 6.10: Proposed performance metrics, resilience index (Todini, 2000), network resilience index (Prasad and Park, 2004), modified resilience index (Jayaram and Srinivasam, 2008), and average pressure of the alternative configurations of Network 2, L – fewer loops, D – larger diameters, S – reduced storage, P – reduced pumping.

<table>
<thead>
<tr>
<th>Network</th>
<th>Rel</th>
<th>Vul</th>
<th>Res</th>
<th>Con</th>
<th>PI</th>
<th>RI</th>
<th>NRI</th>
<th>MRI</th>
<th>Avg P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net 2</td>
<td>0.70</td>
<td>0.45</td>
<td>0.66</td>
<td>0.94</td>
<td>0.66</td>
<td>0.45</td>
<td>0.41</td>
<td>0.48</td>
<td>52.38</td>
</tr>
<tr>
<td>Net 2 L</td>
<td>0.68</td>
<td>0.45</td>
<td>0.66</td>
<td>0.92</td>
<td>0.66</td>
<td>0.39</td>
<td>0.37</td>
<td>0.44</td>
<td>51.77</td>
</tr>
<tr>
<td>Net 2 L,D</td>
<td>0.77</td>
<td>0.50</td>
<td>0.72</td>
<td>0.92</td>
<td>0.71</td>
<td>0.62</td>
<td>0.59</td>
<td>0.66</td>
<td>55.79</td>
</tr>
<tr>
<td>Net 2 S</td>
<td>0.78</td>
<td>0.36</td>
<td>0.80</td>
<td>0.94</td>
<td>0.68</td>
<td>0.85</td>
<td>0.77</td>
<td>1.90</td>
<td>99.34</td>
</tr>
<tr>
<td>Net 2 S,L</td>
<td>0.77</td>
<td>0.28</td>
<td>0.80</td>
<td>0.92</td>
<td>0.63</td>
<td>0.82</td>
<td>0.77</td>
<td>1.86</td>
<td>98.53</td>
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<tr>
<td>Net 2 S,L,D</td>
<td>0.82</td>
<td>0.45</td>
<td>0.85</td>
<td>0.92</td>
<td>0.73</td>
<td>0.92</td>
<td>0.87</td>
<td>2.04</td>
<td>104.28</td>
</tr>
<tr>
<td>Net 2 S,P</td>
<td>0.78</td>
<td>0.41</td>
<td>0.78</td>
<td>0.94</td>
<td>0.69</td>
<td>0.79</td>
<td>0.72</td>
<td>1.32</td>
<td>78.10</td>
</tr>
<tr>
<td>Net 2 S,P,L</td>
<td>0.76</td>
<td>0.34</td>
<td>0.78</td>
<td>0.92</td>
<td>0.66</td>
<td>0.74</td>
<td>0.70</td>
<td>1.26</td>
<td>77.01</td>
</tr>
<tr>
<td>Net 2 S,P,L,D</td>
<td>0.83</td>
<td>0.45</td>
<td>0.86</td>
<td>0.92</td>
<td>0.74</td>
<td>0.88</td>
<td>0.84</td>
<td>1.45</td>
<td>82.96</td>
</tr>
</tbody>
</table>

Given the failure of this case of Network 2 to maintain stable efficiencies, further modifications were made to the system in order to improve its performance and investigate the effects of tank and pump sizing on system operation. These are the reduced storage, and reduced storage and pumping cases, described before.

Reducing storage in Network 2 resulted in a more stable operation under normal conditions since less flow is being directed to tanks and dissipation is reduced. Nevertheless vulnerability increased, as there is less storage to meet the extra demands during peak hours. Overall, the average efficiency, 78% is higher than in the original case with more storage, 70%. The energy supplied by pumps increased more than two-fold (Table 6.9), yet the first case uses more tank supply and is not representative of a full cycle of operation. Pressures are also higher in the second case, yet less energy is dissipated.

Simply reducing storage increased energy requirements as less storage is available to meet demands. Furthermore, pressures almost doubled as pumps were now oversized for the given
flow. Therefore, a third variation of the system, with reduced pumping capacity as well as reduce storage, was modeled. This significantly reduced pumping requirements and average network pressures, yet did not affect the reliability of the network (Table 6.10). Efficiencies remained stable and vulnerabilities, minimum efficiencies, even increased.

For each storage and pumping case, three pipe configurations were modelled, looped, fewer loops, and fewer loops with increased diameters. In every case the proposed performance index and the resilience indices defined by Todini (2000), Prasad and Park (2004), and Jayaram and Srinivasam (2008) followed the same trend and assigned the configuration with fewer loops and increased diameters the best value. This trend is also observed by simply comparing network reliability, i.e. average energy efficiency, or even average network pressure.

When comparing the different storage and pumping cases, the resilience indices are higher for the case with reduced storage, which experiences notably higher pressures. Because these indices are proportional to power surplus, they are partial to higher pressures, even if these are excessive. Even though the performance indices are similar for these three cases, the reduced storage and pumping case slightly outperforms the others. This is due to its higher resilience and reliability.

Overall, as expected, the performance and resilience indices confirm that networks with greater pipe redundancy perform better. The creation of loops or increase in pipe diameter not only decreases head loss but also reduces its variation. The standard deviation of head loss per km of pipe was found to decrease in these configurations for both example networks. Redundancy at tanks and pumps can increase system efficiency, yet different from pipes, they must be controlled according to operational scenarios. Storage can be used to offset pumping during peak hours and maintain efficiency and pressure levels, as shown in the example network 1. Nevertheless, tank inflow must be managed in order avoid high dissipation and low pressures, as in the original case of the example network 2. Therefore, increasing storage and pumping might not necessarily increase performance.
6.4 Critical Appraisal

The proposed performance index is based on the assumption that the performance of water distribution networks does not depend only on the ability to deliver adequate flows and pressures, but also on its efficiency in doing so. Previous measures equate demand satisfaction to performance and apply surrogate reliability measures that are proportional to pressure surplus. The present chapter argues that above safe operating levels of pressure, higher pressures might not translate directly to higher performance.

The applications to the example networks in the previous section show that the resilience indices consistently follow the same trend and vary to a similar degree as the average network pressure. Although the performance index generally follows this same trend, it varies differently and can even be similar for networks with distinct average pressures, as observed in network 2. Therefore, this enables the comparison of the performance of networks that maintain different, yet safe, pressures. Minimum pressure standards vary internationally, and operational standards can even vary locally according to utility practices.

The performance index integrates three energy efficiency metrics and a network demand connectivity metric. Because they represent the efficiency in delivering demand and pressure they vary between 0 and 1 and have a physical interpretation, as does the aggregate index. The metrics capture the range of performance of the network. Furthermore, because these metrics comply with the energy and mass balance of the network, they can be applied to any system. Herein, the performance index was applied to two example networks in order to initially assess the method and compare it to previous studies. Nevertheless, the metrics can be applied to the analysis of real water systems with more scenarios, including potential simultaneous failure.

Even though the performance index consistently followed the same trend as the reliability and resilience of the example networks, the vulnerability and connectivity metrics helped distinguish between networks with similar average efficiency. In the present study, the metrics received equal weighting in the performance index. This can readily be altered to better reflect the priorities of decision-makers and stakeholders. Using a single performance index can also be
controversial if it oversimplifies system conditions. Nevertheless, it can facilitate comparisons and if used in decision-making, this index would be part of a multi-objective analysis including other measures and constraints. Therefore, balancing four additional performance metrics, instead of one adds unnecessary computational costs.

6.5 Conclusions

An efficiency-based performance index is proposed. Unlike previous reliability and resilience metrics, which evaluate the network’s ability to deliver a given set of flows and pressures, the new measure also emphasizes the efficiency of this delivery. The index integrates four sub-metrics: reliability, the average efficiency of the network under all conditions; vulnerability, the minimum efficiency of the network; resilience, average efficiency after a period of failure (vulnerability); and connectivity, minimum percentage of flow delivered despite a pipe burst.

This index was applied to the analysis of two example networks with different configurations and compared to previous resilience indices. All of the indices indicated, as expected, that increasing pipe redundancy, whether through larger pipe diameters or additional loops, increases performance. Not only does it increase efficiency, it also reduces its variability. The redundancy of pumps and tanks, however must be controlled according to demands in order maintain pressures and efficiencies.

Although the proposed index generally follows the same trend as the previous indices, such as generally increasing with network pressure, it varies differently in important ways. For instance, it is not unduly responsive to power surplus and is able to compare networks that efficiently maintain different, yet safe, levels of pressure. Furthermore, because it is based on efficiency metrics, it has a direct and simple physical interpretation. This also indicates that the index complies with the energy and mass balances of the network. It can, thus, be applied with reasonable confidence to real networks. Even though the index was provisionally applied to only three demand scenarios (normal, fire, and pipe burst), it can be easily be applied and adapted to multiple scenarios, including simultaneous failures.
7 Cost Gradient Search Optimization Technique

Previous chapters have explored elements that influence water distribution system design and operation, as well as proposed metrics to assess and compare the efficiency and performance of these systems. The present chapter is concerned with the design process itself. As made clear in the preceding chapters, inputs to the design process, such as future demands, are uncertain, and the objectives of the design are diverse.

Recent studies have focused on developing complex optimization techniques for simple hypothetical networks, which rarely account for multiple loading conditions and generally concentrate on minimizing capital and operational costs. These techniques are seldom applied to real systems, perpetuating a gap between research and practice. Accordingly, this chapter seeks to define a simpler technique that can be used to select pipe sizes that minimize capital, operational, and damage costs of networks with varying loads. The intention is that it be applied as part of a broader optimization process and that its lower computational intensity allow for the analysis of more storage, pumping, and control scenarios.

The present chapter is based on the manuscript entitled “Cost Gradient Search Optimization Technique for Water Distribution Networks with Varying Loads” by Rebecca Dziedzic and Bryan Karney, submitted to the Journal of Water Resources Planning and Management. It addresses the issue of high computational expenses in optimizing water network design, specifically with regards to pipe sizing and modelling long-term costs of system with varying demands.

7.1 Introduction

It should be self-evident that water distribution models are simplified representations of reality, not facsimiles of these complex systems. Until recently, however, the development of optimization techniques has largely focused on increasingly intricate and complex algorithms to optimize hypothetical networks, an approach that has tended to neglect various uncertainties and
objectives of real water distribution systems. The present study naturally accepts the use of models of hypothetical networks to test optimization methods, but advocates caution and systems thinking. A theme is that the data acquisition and computational efforts of meticulously analyzing variations of one variable in lieu of broader multi-variable fluctuations should often be viewed with healthy skepticism.

Various studies have minimized specific costs of water distribution networks under one average demand scenario (Schaake and Lai, 1969; Alperovits and Shamir, 1977; Fujiwara and Khang, 1990; Samani and Naeeni, 1997; Savic and Walters, 1997; Gomes et al., 2009; Haghighi et al., 2011). In order to maintain pressures within safe ranges as established by standards, either constraints are set on solutions or objective function penalties are incorporated. However, networks designed on a purely cost effective basis and for a single loading condition tend to be driven to a branched, less resilient, layout. Thus, researchers have used a minimum diameter constraint (Alperovits and Shamir, 1977), applied measures of resilience (Todini, 2000), or assessed multiple loading conditions (Walski, 1987), in order to produce appropriately looped network designs the real systems require for robust and reliable operation. However, greater realism usually comes with a high computational price.

Given these goals and limitations, the present study proposes a more computationally efficient optimization technique for water networks but one that effectively includes multiple loading conditions. In order to do so it seeks to shorten or compress the extended period analyses needed to assess the long-term costs of these systems with varying demands. However, the authors readily acknowledge that because the current technique only optimizes the sizing of network pipes, as indeed have many other optimization techniques, it is meant to be applied as part of a broader optimization and assessment process. Its lower computational cost readily allows generalizations and for the comparison of more storage, pumping, and control alternatives, which have in practice typically relied on engineering judgment and experience.
7.2 A Brief Literature Review of Optimization Techniques

Walski (2001) cautions against the limitations of optimization based on cost minimization: (1) it is difficult to identify true benefits and constraints because of uncertainties, especially those pertaining to future demands; (2) actual demands are influenced by pipe sizing, meaning that design becomes a “self-fulfilling prophecy; (3) many alternatives will have virtually the same net benefits. Approaches for overcoming each of these limitations are suggested hereafter.

The very nature of the design of water networks is fundamentally demand driven. Although predicting long term future demands is recognizably difficult, water distribution networks are designed to be robust, wherein small variations in demand do not greatly affect performance. Probable ranges of demand can be modeled in order to simulate hourly to yearly variations in flow. Greater changes to average demands, caused by leakage control or conservation programs, for instance, can be assessed as different alternatives since they are part of a broader multi-stakeholder decision-making process such as the construction of tanks and pump stations. Furthermore, in reality, distribution networks are generally not built in a single stage, but rather are gradually expanded as the population grows and the city develops. This allows for a somewhat continuous revision of expected future demands given historical flows. Creaco et al. (2014a) and Creaco et al. (2014b) accounted for construction phasing in their design of water distribution networks, which yielded better results than single flow analysis. It enabled short term construction upgrades while minimizing long term costs.

Secondly, demands are influenced by a number of factors, including network design, which affects pressure, and thus leakage and pressure dependent demands. Therefore, the installation of larger pipes and loops generates benefits that might not be modeled. In order to account for some of these benefits, Todini (2000) applies a resilience index to guide the optimizations of networks, while Creaco et al. (2014c) combine this with a loop uniformity index to assess network reliability. Babayan et al. (2005) design networks according to different levels of robustness. Filion et al. (2007) define expected annual damages based on pressures. Other external factors that affect demands include population growth, land-use changes, conservation programs, and
rate structures (Giacomini et al., 2013). These can be modeled as different scenarios and incorporated in system planning.

Thirdly, not only because multiple alternatives might have similar costs, but because the sustainability of water distribution systems depends on other factors than simply minimizing costs, evaluation should ideally involve other objectives. The sum of pipe and pumping costs, used in various optimization studies, does not even fully represent costs, much less the full objectives of water distribution systems. Including a measure of damage or failure costs can provide a more complete picture and better consider infrastructure performance (Filion et al., 2007). More recently, Marques et al. (2014) applied the concept of real options to optimize water distribution networks while comparing different future scenarios. Each potential decision path in the planning horizon is optimized through simulated annealing and compared according to capital costs as well as a regret term, intended to represent the uncertainty of each scenario. Thus, network models can be attached to broader system analyses, which might contemplate climate change effects, policy revisions, or user expectations.

The focus on select costs, however, is not a unique feature of water distribution models, and is a paradigm that must be revised throughout the system. Many utilities make short-term financial plans that potentially convey the benefits of deferring expansions through demand management. Yet, oftentimes, these fail to evaluate the broader social and environmental benefits of water availability, as well as the external costs incurred. For instance, external costs might include healthcare consequences due to the delivery of higher risk water, or the imposed transportation, infrastructure, and private property costs due to, say, water main bursts or system repairs. System failures can have significant and wide-ranging costs.

Nonetheless attempting to represent all benefits and costs monetarily is impractical. Certain valuations, say of ecosystems or even of human lives, are notoriously complicated. The present research does not presume to resolve this debate; it outlines one approach and discusses its limitations. It is obvious, however, that network optimization studies, including the current one, seldom represent all costs or fully account for the multiple infrastructure, social, and environmental objectives. Instead of modeling a myriad of possibilities, the present study
proposes a more computationally efficient gradient optimization algorithm that can be used to compare scenarios.

Evolutionary programming techniques, specifically genetic algorithms (GA), have been widely studied for water distribution network optimization (Savic and Walters, 1997; Tolson et al., 2004; Haghighi et al., 2011). The extension of these models to consider multiple loadings does not cause the search convergence speed to deteriorate, according to Savic and Walters (1997), but it would further increase run time. Simpson et al. (1994) optimized an example network with three demand patterns, two of which were fire-loading cases. Babayan et al. (2005), instead, define a probability density function for the network demands and estimate pressures through numerical integration.

Gradient search techniques are less frequent in water network optimization studies. Monbaliu et al. (1990) propose a rule based search method. Pipes are initially set at their minimum diameters. After each iteration, the diameter of the pipe with maximum head loss per unit length is increased to the next available size, until pressure requirements are met. Todini (2000) applies a cost gradient, the reduction in cost per unit of power dissipation for one step in commercial diameters. The diameters case are initially set to their maximum values, and reduced until velocity or resilience constraints are just met. Gomes et al. (2009) also apply a cost gradient technique and note that it generates satisfactory results for a fraction of the computational cost of many other methods. Neither of these, however, was applied to networks with multiple loads. According to Eusuff and Lansey (2003), it is difficult to ensure the effectiveness of this type of greedy algorithm because of complex system interactions. Nevertheless, this has convincingly shown that it can yield near optimal solutions for water networks.

In order to increase the computational efficiency and uptake of these optimization techniques, studies have sought to reduce the search space, decrease the number of function evaluations, or to simplify the evaluation of the objective function. Tolson et al. (2009) propose a hybrid discrete dynamically dimensioned search. Two local heuristic search techniques that evaluate one pipe and two pipe changes relative to the current best solution are combined with a dynamically dimensioned search. This algorithm is more efficient because it only requires
hydraulic simulations for a fraction of the solutions evaluated. Compared to the Max-Min Ant System (Zecchin et al., 2007), Genetic Algorithm Pipe Network Optimization Model (Reca and Martinez, 2006), and Particle Swarm Optimization variant (Montalvo et al., 2008) techniques, the method reduces computation time to about half.

Di Pierro et al. (2009) tested two efficient hybrid algorithms: a Pareto Efficient Global Optimization (Knowles, 2006) process and a Multi-Objective Learnable Evolution Model (Michalski, 2000). The first approximates the objectives and takes into account the predicted value of the solution as well as the prediction error when searching for solutions, thereby reducing computational costs. The latter also limits the number of function evaluations. It integrates a symbolic learning component that is used to classify solutions. These methods were found to reduce the number of simulations by at least 10%, compared to a Pareto Envelope region-based Selection (Corne et al., 2001).

Fu et al. (2012) seek to reduce the search space by applying a global sensitivity analysis (Sobol, 2001) combined with a epsilon non-dominated sorted genetic algorithm (Kollat and Reed, 2006). Compared to a full search, the analysis reduced the number of function evaluations by 60 to 70%. Zheng and Zecchin (2014) apply a different strategy to simplify calculations. The network is decomposed then each sub-network is optimized and combined for a second optimization. Partitioning the network reduced computational time by approximately 90%.

Given the need to compare new, more efficient techniques, to existing methods, these should be applied to the same network. One of the benchmark networks which has been widely studied is the “Anytown” example (Walski et al., 1987). The problem was originally solved by participants of “The Battle of the Network Models” workshop (Gessler, 1985; Brill et al., 1985; Morgan and Goulter, 1985; Ormsbee, 1985). Their models only optimized pipe sizing. Pump and tank location and sizing were selected using engineering judgement and manual calculations. Brill et al. (1985) and Morgan and Goulter (1985) applied linear programming models, Ormsbee (1985) used a box-complex search method, and Gessler (1985) applied selective enumeration of a pruned search space. The latter yielded the lowest costs, but the effectiveness of the models
could not be directly compared since each study located the tanks on different nodes. Computer
time was not compared.

Walters et al. (1999) applied a structured messy genetic algorithm (SMGA) to the Anytown
problem. The complete problem, including pump and storage location and sizing, was modeled.
This increases the number of variables by at least 32. The objective of the method is not only to
minimize capital and operational costs, as defined in the original problem, but also maximize
benefits, defined as the remediation of low pressures and storage shortfalls. The program was run
three times, each with 50,000 solution evaluations. Farmani et al. (2005) also applied a SMGA to
the complete Anytown problem. Instead of calculating benefits, a resilience index is considered
as the second objective. This model was only run for 5,000 generations.

Fu et al. (2013) use an epsilon non-dominated sorted genetic algorithm (ε-NSGAII) in
optimizing the complete problem, but define six objectives involving capital cost, operating cost,
hydraulic failure, leakage, water age, and firefighting capacity. This naturally increases
computational time. Five random seeds trials were run, corresponding to 5 million model
simulations, representing a computational effort of about 180 hours using a desktop with a 3
GHz processor in Windows XP. Fu et al. (2012) combined the ε-NSGAII with a global
sensitivity analysis in order to reduce the search space of the Anytown problem. In this case,
costs were balanced with a resilience index. Ten random seeds trials were run, equivalent to 1
million model simulations, which took about 300 h on a desktop with a 3 GHz processor in
Windows XP.

Ostfeld (2012) decomposes the problem and applies an ant colony algorithm. Only pipe sizes of
a modified Anytown network were optimized. The computational time varies according to the
colony. In this case at least 8 runs totaling 25 h on a notebook with a 2.26 GHz processor were
needed to reach a feasible outcome. This lower computational intensity is partly due to the
simplification of the problem, and partly due to its decomposition. The range of computational
time necessary to optimize the Anytown problem through different methods shows how the
number of objectives and random seed trials greatly affects computational costs. Even the
simplest methods, if applied to a case at least as complex as Anytown, require more than a day of modeling.

7.3 Methodology

The proposed method seeks to reduce the computation time of optimizing water distribution networks with varying demands. It applies a gradient search and approximates the objective function by shortening the extended period analysis. The design improvement process, outlined in Figure 7.1, begins with specifying the demand series, which may be deterministic or stochastic, and the damage probabilities for different pressure states. The demands within the defined shorter time cycle $t_c$ should match the probabilities of the demands in the full analysis period, and their variation. In the case study, for instance, the daily demand pattern was maintained, yet long-term growth was accelerated. The optimization process, thus, assumes that a shorter period of time can be selected to estimate, with sufficient precision, the hydraulic variations of the system and costs of the entire period.

The objective of the process is to minimize long-term costs as defined in (7.1),

$$C_T = E_{Sup} \cdot C_E \cdot T + C_D + C_C$$

(7.1)

where $C_T =$ total costs, $E_{Sup} =$ energy supplied by pumps, $C_E =$ energy cost ($/kWh); $T =$ analysis period (hrs); $C_D =$ damage costs; and $C_C =$ capital costs.
Figure 7.1: Algorithm for iterative dynamic optimization of water distribution networks.
Table 7.1: Damage function for Anytown example based on Filion et al. (2007).

<table>
<thead>
<tr>
<th>Pressure range (m)</th>
<th>Conditional probability (per day)</th>
<th>Average damages (SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P &lt; 14.0</td>
<td>1/3,650</td>
<td>fire</td>
</tr>
<tr>
<td>14.0 ≤ P &lt; 26.0</td>
<td>1/10</td>
<td></td>
</tr>
<tr>
<td>26.0 ≤ P &lt; 30.0</td>
<td>1/10*(30-P)/4</td>
<td></td>
</tr>
<tr>
<td>84.0 ≤ P &lt; 88.0</td>
<td>1/25*(P-84)/4</td>
<td></td>
</tr>
<tr>
<td>P ≥ 88.0</td>
<td>1/25</td>
<td></td>
</tr>
</tbody>
</table>

Damage costs are computed according to the pressures found in the hydraulic simulation. The costs and probabilities for each pressure range were applied based on the definitions of Filion et al. (2007). Three types of damages are considered: type-1 damages occur when the pressure head falls below 14.0 m at a node and a fire erupts simultaneously; type-2 damages occur when the pressure head is between 14.0 and 26.0 m at a node, causing (say) backup pumps on surrounding industrial properties to fail; type-3 damages occur when pressure head at a node rises above 88.0 m, potentially leading to a pipe burst. While Filion et al. (2007) applied uniform damage probabilities for each pressure range, the present study also established adjacent pressure ranges where probabilities and damage costs decrease linearly (Table 7.1). This more staged approach not only better resembles real conditions but tend to guide the gradient search.

After defining the demand series and costs, the loads and initial network design are entered into the EPANET2 network solver (Rossman, 2000). The simulation computes pressures and flows at nodes and links. The nodes downstream from each link are then successively identified at each time step, so that the pressure effects of altering pipe diameters can be assessed. At each iteration, corresponding to one time cycle of the simulation, the ratio between the gradients of energy dissipation costs, damage costs, and pipe costs is calculated, as indicated in (7.2),
\[ r_{i,j} = -\frac{(E_{\text{Dis},i,j} - E_{\text{Dis},i,j+1}) \cdot C_E \cdot T + C_{D,i,j} - C_{D,i,j+1}}{C_{P,i,j} - C_{P,i,j+1}} \] (7.2)

where \( E_{\text{Dis}} \) = energy dissipated (kWh); \( i \) = current pipe flows; \( j \) = current diameter; \( j+1 \) = next available diameter (larger or smaller); \( C_P \) = pipe costs.

The ratio is intended to reflect the financial return of investing or disinvesting in pipes. In other words, the ratio indicates the degree to which other costs, energy and damage, are expected to increase or decrease given a change in diameter. If pipe diameter is increased, capital costs grow and this investment would only be worthwhile if other costs, such as energy or damage, are reduced. Accordingly, the ratio should be greater than 1, in order for a particular increment in pipe diameter to be beneficial. Conversely, if pipe diameter is decreased, energy and damage costs should increase less than the reduction in capital costs, and the ratio should be less than 1.

Accordingly, at each iteration the pipes with the minimum and maximum cost gradient ratios are identified. The pipe with minimum cost ratio, if below 1, is downsized, whereas the pipe with maximum cost ratio, if above 1, is upsized. Sizing is altered to the next commercial pipe diameter. In order to avoid extremely low or high pressures, diameters are also altered if they surpass constraints even if the cost gradient is unfavorable.

The ratio only considers the primary variables that are expected to change given the adjustment of pipe diameters. The normally reasonable assumption here is that adjusting one pipe diameter by one commercial size only marginally affects the flow distribution or the pumping requirements. Pressures downstream of the altered pipe are recalculated based on this new demand distribution in order to estimate the revised costs. Nevertheless, after each iteration the modified network is simulated again and the new distribution is calculated to confirm that the expected improvement occurs, or to backtrack and undo the modification.

Energy costs are expected to change solely due to modified head losses in the adjusted pipes. Alternative damage costs are computed with recalculated pressures, assuming that flows are maintained and only pressures at the nodes downstream of the modified pipe are affected.
Furthermore, it is emphasized that for the current exploration the only component of capital costs that is altered is pipe costs. All costs are extrapolated for the analysis period and discounted to reflect their present value.

### 7.4 Anytown Case Study

The proposed method was applied to the Anytown system of Walski et al. (1987). In addition to being well studied, and having a realistic topological complexity, the Anytown problem accounts for demand variations (hourly changes and population growth), fire flows, as well as capital and operational costs. Full details of the system are given in Walski et al. (1987) but are summarized here for convenience.

The problem consists of proposing new tanks, pumps, as well as pipes that will be laid in a new area of the city or parallel to existing pipes, in order to meet demands over the next 20 years. Demands vary throughout the day, yet not seasonally, and grow at different rates, depending on the location.

In the present study only pipe sizing was optimized, the tank location and sizing recommended by Gessler (1985) was applied. A schematic representation of the Anytown network is presented in Figure 7.2. Pipe sizing was optimized given three options, each with different costs, as defined in the Anytown problem (Walski et al.,1987): installing new pipes (links 54, 68-76); paralleling old pipes in residential areas (links 36-66); and paralleling old pipes in urban areas (links 2-34, 48). This amounts to 35 pipe diameter variables, each with 10 potential discrete diameters.

Pipe, tank, and pump costs depend on dimensions and location. Following other studies, the cost of energy is fixed at 0.12 $/kWh, the an annual interest rate at 12%, and the amortization period at 20 years. While the original Anytown problem does not require the computation of damages, it sets minimum pressure constraints. Herein, the same interest rate and period were applied to damage costs.
Although internal pipe roughness would be expected to change over the analysis period, this is not contemplated by the traditional Anytown example. The hypothetical network of Anytown (Walski, 1987) contains a number of assumptions that limit its general applicability. It does not contain all of the features of real systems (e.g., multiple pressure zones, seasonal and local demand fluctuations, pressure dependent demand, fiscal constraints, uncertainty of future demands and pipe roughness, and construction staging). Nevertheless, its multiple loads, pumps, and tanks, complex topography and location dependent pipe costs make it a challenging (and well known) benchmark for optimization models.

Figure 7.2: Anytown network of Walski et al. (1987) with additional tank proposed by Gessler (1985).

A time cycle $t_c$ of 100 days was applied in the optimization procedure to represent demand variations. Significantly, extrapolating these short-term results was found to accurately depict the costs of the full 20 year analysis period. Daily demand patterns were maintained in the simulation cycle, yet growth was accelerated so that maximum demands are reached by day 100. Fire flows were set to the values in Walski et al. (1987) with a probability of 0.10 fires per year,
as suggested by Filion et al. (2007). The occurrence of fires during the simulation time cycle $t_c$ is stochastically established with a random number generator.

Although hourly time cycles clearly do not fully represent the variation of flows during the analysis period and may not produce uniformly accurate good results, the assertion here is their advantages outweigh their faults. That is, that a “compressed” approach to time variations can be used to generate useful approximations to a more generally valid solution, thus creating a provisional solution that can significantly speed the overall optimization process. Accordingly, hourly iterations were initially used to generate a rough solution which was then optimized with the 100 day time cycle $t_c$.

In order to assess the effect of different conditions on the solution, variations of the problem were also optimized. For instance, reduced population growth, consumer water saving, or utility led conservation initiatives could lower water consumption. Damage costs are also inevitable uncertain and depend on the utility’s valuation of damages, its aversion to risk and many other factors include the timing of damage and the ever-changing vulnerability of users. Accordingly, two additional scenarios were optimized, with final demand reduced by 10%, and with doubled damage costs.

### 7.5 Results and Discussion

Results of the optimization process are compared to those of Gessler (1985) in Table 7.2, which assumed the same tank and pump sizing and location. The proposed solution has a total cost of $M 16.5, which only 2% higher than the $M 16.3 cost of Gessler’s (1985) solution. This is due to higher capital costs, which in turn reduce damage costs. Despite this investment in larger pipes, however, energy costs remain virtually unchanged. Walski et al. (1987) also noted the low sensitivity of Anytown energy costs to pipe sizing, except when it affects pump efficiency. Therefore, network optimization, in this case, is largely concerned with selecting the smallest pipe diameters that avoid exceptionally high costs or exceed pressure constraints.
Although the proposed solution does not quite achieve Gessler’s (1985) low cost, it comes quite close using a less computationally intensive process. The reported solution to the original Anytown problem was reached after 24,000 hourly iterations of the gradient technique, that converged to an approximate solution, and subsequent 33 100-day iterations, totaling almost 12 years of hydraulic simulations. Therefore, in order to reach its solution the network was modeled for fewer years than its total analysis period, 20 years. This took about 1.2 h on a notebook with a 1.9 GHz processor in Windows Vista. Compared to previous optimization studies of the Anytown network described in the literature review, even single trials for optimizing pipe sizing, this represents a notable reduction in computational costs. Approximating the objective function through shorter period analyses is a real simplification. This acceleration technique can obviously be applied to other optimization methods too. The decision to apply the proposed gradient optimization method will depend on the complexity of the problem and, thus, the trade-off between computational costs and potential savings.

Table 7.2: Pipe sizes and expected costs for Anytown design solutions: (I) original problem, (II) 10% decreased demand growth, and (III) doubled damage costs.

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Pipe Diameters (mm)</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>12</th>
<th>18</th>
<th>30</th>
<th>32</th>
<th>34</th>
<th>42</th>
<th>44</th>
<th>48</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gessler (I)</td>
<td></td>
<td>1</td>
<td>356</td>
<td>610</td>
<td>1</td>
<td>1</td>
<td>254</td>
<td>1</td>
<td>1</td>
<td>356</td>
<td>457</td>
<td>1</td>
<td>610</td>
</tr>
<tr>
<td>Gradient (I)</td>
<td></td>
<td>356</td>
<td>305</td>
<td>457</td>
<td>305</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>1</td>
<td>1</td>
<td>254</td>
<td>305</td>
<td></td>
</tr>
<tr>
<td>Gradient (II)</td>
<td></td>
<td>305</td>
<td>305</td>
<td>305</td>
<td>406</td>
<td>305</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>1</td>
<td>1</td>
<td>254</td>
<td>254</td>
</tr>
<tr>
<td>Gradient (III)</td>
<td></td>
<td>356</td>
<td>305</td>
<td>457</td>
<td>305</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>1</td>
<td>1</td>
<td>254</td>
<td>305</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2 cont.: Pipe sizes and expected costs for Anytown design solutions: (I) original problem, (II) 10% decreased demand growth, and (III) doubled damage costs.

<table>
<thead>
<tr>
<th>Costs ($M)</th>
<th>52</th>
<th>54</th>
<th>58</th>
<th>60</th>
<th>68</th>
<th>70</th>
<th>72</th>
<th>74</th>
<th>76</th>
<th>Capital</th>
<th>Energy</th>
<th>Damage</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>203</td>
<td>406</td>
<td>356</td>
<td>305</td>
<td>305</td>
<td>152</td>
<td>356</td>
<td>152</td>
<td>5.8</td>
<td>6.8</td>
<td>3.6</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td>254</td>
<td>305</td>
<td>1</td>
<td>152</td>
<td>356</td>
<td>152</td>
<td>305</td>
<td>610</td>
<td>457</td>
<td>6.2</td>
<td>6.8</td>
<td>3.5</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>254</td>
<td>356</td>
<td>203</td>
<td>152</td>
<td>356</td>
<td>152</td>
<td>254</td>
<td>508</td>
<td>406</td>
<td>6.0</td>
<td>6.7</td>
<td>3.8</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>254</td>
<td>356</td>
<td>254</td>
<td>254</td>
<td>356</td>
<td>152</td>
<td>203</td>
<td>610</td>
<td>406</td>
<td>6.4</td>
<td>6.8</td>
<td>6.8</td>
<td>20.0</td>
</tr>
</tbody>
</table>

The various uncertainties regarding the future of water distribution systems also make it more difficult to compare network solutions. Predicted costs are attached to a probability and margin of error, which mean they in fact promise a range of potential future costs. Furthermore, other
decisions taken as immutable in many optimization methods can generate more savings. This undermines the high computational efforts of optimization methods, which might be selecting pipe sizes for systems with sub-par pump and storage design. For instance, the original solutions to the Anytown problem (Gessler, 1985; Brill et al., 1985; Morgan and Goulter, 1985; Ormsbee, 1985) compared by Walski et al. (1987) consist of distinct tank locations and sizes, and incur costs that differ by up to 12%. A non-computationally intensive optimization process, such as the one proposed, could facilitate greater analysis of more design, operation, and management scenarios. If applied as part of a broader optimization process that compares multiple scenarios, it could helpfully supplement engineering judgement and experience.

In order to test the proposed gradient method and evaluate the costs of potential uncertainties, two additional scenarios were optimized: a 10% decreased demand growth (II), and a run with doubled damage costs (III), shown in Table 7.2. Although many other uncertainties exist, these are variables that greatly depend on future infrastructure conditions, user behavior, and utility operations. The increasing focus on water conservation, as an environmental, as well as a cost reducing measure focus on water conservation, as an environmental, as well as a cost reducing measure, has led to lower demands, sometimes unexpectedly, rendering networks overdesigned. Accordingly, if this demand management is planned, the optimal design should differ. As expected, the reduced demand scenario resulted in a network with smaller pipes, but increased damages. Yet, total costs did not differ greatly. Nevertheless, if the network optimized for the original scenario were to experience reduced demands, total costs would be expected to marginally (2%) higher. With doubled damage costs, the proposed gradient method generated a network with larger diameters and reduced damages. Therefore, the optimization technique responded to the system modifications and generated expected adjustments in network designs. Although designs are similar, pipe diameters only differ by one or two sizes, they reflect a different balance between capital costs and damages.

Because fires are stochastically generated in the model, a different random seed can also affect costs, and thus the solution. Altering the set of stochastically generated fires was found to potentially change solution costs by around 2%. The network was also optimized for one set of
fires and checked for another. Similarly, this was found to change costs by approximately 2%. Therefore, the uncertainty in future damages affects the solution and should be investigated in future studies. Nevertheless, the solution performance was shown to be stable with a new set of fires.

7.6 Initial Assessment of the Proposed Methodology

As other heuristic methods, the proposed gradient search technique does not guarantee an optimal solution and is sensitive to the parameters chosen. In the present case, total costs are a function of user demands, fire flows, pipe costs, energy rates, damage costs, and pressure limits. Future energy rates are uncertain and depend on a number of factors, such as available fuels, power generation, weather conditions, regulations, and the global economy. Pressure limits are based on safety standards that vary by system, and transgressing them does not necessarily translate into real damages. Damage costs, applied less in other optimization methods, depend not only on the network and its operations, which affect the probability of damages, but also on stakeholder valuation of damages, particularly for those sustained by humans.

The damage costs suggested by Filion et al. (2007) and applied herein comprise three types of damages: loss of life and property, interruption of industrial production, and damage to system pipes. The problem, as currently formulated, thus balances potential costs of loss of life with system costs, which is controversial. Nevertheless, other methods do this, yet implicitly by balancing costs with pressures, resilience, or reliability. Decision makers should, thus, understand and make explicit the assumptions attached to pressure limits and costs. These should be established according to system properties and stakeholder risk aversion.

If applied to a real network, the proposed method would require the assessment of the damage probability density functions, and an evaluation of damage costs. Future studies can analyze these system properties and perhaps identify commonalities that can facilitate approximations. This information would not only be useful in the design phase, as applied here, but also during
operations and planning. Other costs would need to be included in real system decision making as well, such as water treatment, maintenance, and environmental damages.

The proposed optimization technique has a positional bias, which means the final solution is influenced by the initial design. Because pipe sizes are set to their maximum value in the initial iteration, solutions tend towards larger pipe diameters. This, nevertheless, generates more robust networks. Furthermore, the short time cycles used to represent the full analysis period, slightly overestimate damages since demands vary more often, which also leads to larger diameters. In order to reduce these discrepancies, more initial designs could be used as well as longer time cycles. However, the parameters applied herein generated near optimal solutions with lower damage costs than Gessler (1985). In other applications, these will need to be chosen according to the complexity and demand variation of the system.

The cost gradient technique seems more intuitive than many optimization methods, facilitating its application and adaptation by water utilities. Because it is also less computationally intensive than most other methods, more scenarios and alternatives can be assessed, enabling utility decision-making, which is obviously concerned with more than pipe sizing, infrastructure costs, and energy costs. Different from other gradient techniques, the present method accepts varying loads. Furthermore, its inclusion of damage costs helps balance system costs and resilience.

The proposed method extends previous optimizations processes. Nevertheless, the optimization of water distribution systems, due to their complexity, is inherently challenging. The core concept of optimization, that of achieving the “best” solution, is clearly disputable. The long life cycle of the infrastructure and its interaction with an evolving and highly human context produce multiple uncertainties. The models that represent this reality must balance tensions between simplicity and accuracy, generality and specificity, internal and external parameters (i.e., what is included in the model and what is asked of it), as well as accepted and rejected conditions (i.e., what of the system is accepted and modified by applying the model).
7.7 Conclusions

A cost gradient search technique is used to iteratively model long-term network hydraulics with varying loads using shorter time cycles and to adjust pipe diameters in order to minimize system costs (capital, operational, and damage). The research extends previous studies of capital-cost single-load gradient techniques and those with expected annual damages, in order to develop a less computationally intensive optimization method. When applied to the well-known network of Anytown, results indicated that shorter time cycles can be used to approximate full period costs. Additionally, the technique can be applied to different scenarios and can generate near optimal solutions. It is, thus, useful in cases where more computationally intensive methods are infeasible or cannot generate much greater savings, such as optimizing pipe diameters of complex systems with varying loads, and comparing multiple strategies (infrastructure, operational, and management). Future studies are required to apply the proposed technique to real systems in order to further verify its usefulness and applicability. Furthermore, a detailed study of system uncertainties and their effect on system costs must eventually be performed in order to better prioritize computational efforts.
8 Conclusions and Future Steps

This thesis seeks to take a metaphorical step back in order to gain a panoramic view of the water supply system and better align the research with utility needs. The need for a better understanding of not only the infrastructure, but also of system requirements, risks, costs and stakeholders becomes clear from this view. Previous chapters have studied different components of water distribution systems, and their connections. They only begin to explore the complexities that abound within these systems, but they address the main current issues from a systems perspective by analysing system interconnections and applying readily available resources.

The proposed tools were envisioned to address current issues of North American water distribution systems, particularly those in Ontario, Canada, and to lessen the gap between research and application. Accordingly, they were developed to be applied by engineers, planners, and managers with current modeling and data collection practices. The issues addressed by them include water scarcity, disconnection between utilities and stakeholders, inefficient energy use, failure to comprehensively assess infrastructure performance of complex systems, and high computational expenses of optimizing water network design. These are each related to a gamut of other issues, such as leakage, aging infrastructure, high expansion costs, and short-termism. Nevertheless, the tools are not meant to solve all problems faced by water distribution systems, but to begin to shift perspectives, address important issues systemically, and motivate the quest for sustainability. Accordingly, the key message of this study is the benefit of applying systems thinking to the development of new solutions for sustainable water distribution systems.

8.1 Summary of Contributions and Conclusions

The major contribution of the thesis to the field of water distribution system analysis has been the development of tools that take into account the complex interconnections of these systems and facilitate decision-making by collecting, integrating, analysing, and re-interpreting readily available data and models.
Each chapter or tool has led to specific contributions, described below.

1. Chapter 2 compares different definitions of sustainability and argues that the various connections between objectives of sustainable systems call for integrated approaches. In order to facilitate a systemic analysis, the connections between components of water distribution systems are mapped. This facilitates the visualization of feedback loops, hubs, and potential cascade effects. Subsequent chapters explore how these connections can inform decisions, and how the decisions affect the connected components.

2. Chapter 3 proposes an approach for water demand management. The chapter is based on the manuscript entitled “Building an Integrated Water-Land Use Database for Defining Benchmarks, Conservation Targets, and User Clusters”, published in the *Journal of Water Resources Planning and Management*, and reproduced with permission from ASCE. The issue of limited water resources is addressed by identifying factors that motivate water consumption and users that consume more water than expected, given their characteristics. Demographic, land use, and water consumption data are linked in an integrated database, which is used to define water use metrics, benchmarks, conservation targets, and customer segments. The approach was applied to the cities of Barrie, Guelph, and London, ON. The metrics are shown to normalize water consumption and facilitate the comparison of water use between sectors or even utilities. The benchmarks and conservation targets further facilitate demand planning and communication regarding conservation. Furthermore, customer segments are defined through a clustering analysis which indicates that users within the same or similar property code tend to cluster together. Therefore, property codes can be used to classify customers if more detailed data is not available.

3. Chapter 4 develops a survey for collecting user feedback on expectations of service in order to gauge the correlation between user and utility concerns, and support the improvement of the water utility’s business model. The chapter is based on the manuscript entitled “Collectively Re-envisioning the Water Utility Business Model”, submitted to *Water Resources Management*. It furthers the analysis of the demand side
through qualitative research. Questions relate to user demographics, characteristics, awareness, concerns, motivations, priorities, communication, and water system related preferences. The survey was conducted with residential water users in the City of Guelph, ON. As expected, results highlight user concern with water scarcity, an issue that has been regularly addressed by the local utility and is the focus of the City’s latest Water Supply Master Plan Update. Nevertheless, other issues were also identified, such as concerns with water quality, aging infrastructure, and costs, as well as low awareness of many system components, calling for further attention by the utility. Furthermore, different user types were found to prefer distinct communication channels, confirming the need for alternative channels in order to reach and receive feedback from users. The business model perspective, applied in discussing results and potential improvements to the utility, was found to motivate a systems approach and warrant a deeper understanding of the users and the service they require.

4. Chapter 5 proposes energy metrics in order to assess the energy efficiency of water networks and their components. The chapter is based on the manuscript entitled “Energy Metrics for Water Distribution System Assessment: A Case Study of the Toronto Network”, submitted to the *Journal of Water Resources Planning and Management*. The metrics describe how energy is supplied, dissipated, lost, and delivered, throughout the system, on both a local and global (system-wide) scale in different operational scenarios. These are not only indicators of electricity use, but also of system capacity, efficiency, burst potential, and greenhouse gas emissions. Furthermore, the comparison of component metrics allows for the identification of specific pipes, tanks, or pumps where changes would be most beneficial. The proposed energy metrics were applied to a case study of the Toronto water distribution system. Significantly, results indicate that, on average, less than 27% of energy supplied to the system is delivered to the users in the form of pressure and flow. This inefficiency has important economic and environmental repercussions. Nevertheless, it was found that changes to operations, such as pump scheduling, could increase efficiency without considerably affecting system pressures.
5. Chapter 6 proposed performance metrics for assessing the performance of networks with multiple loading conditions. The chapter is based on the manuscript entitled “Performance Index for Water Distribution Networks Under Multiple Loading Conditions”, submitted to the Journal of Water Resources Planning and Management. The metrics represent system reliability, vulnerability, resilience, and connectivity. These are themselves based on the energy efficiency, hydraulic capacity and structural ability of the system to deliver water under a range of conditions. The metrics were applied to two example networks and variations of these, enabling the assessment of their relevance, their sensitivity to system changes, and permitting a comparison to existing metrics. The proposed performance index generally follows a similar trend as the existing indices, increasing with network pressure. Nevertheless, it varies differently and penalizes networks with unnecessarily high pressures. Because the index is based on energy and demand efficiency metrics, it automatically complies with the energy and mass balances of the network. Moreover, the new metric is easily interpreted and can be applied to various systems, whether complex or involving multiple scenarios.

6. Chapter 7 presents a cost gradient search technique that optimizes pipe sizing of networks with varying loads. The chapter is based on the manuscript entitled “Cost Gradient Search Optimization Technique for Water Distribution Networks with Varying Loads”, submitted to the Journal of Water Resources Planning and Management. It seeks to reduce the computation time of optimizing water distribution networks with varying demands by using a sequence of shorter time cycles to approximate a fuller range of costs. This should facilitate the application of the method to a broader optimization process through which multiple strategies (infrastructure, operational, and management) are compared. The technique was applied to the well-known network of Anytown. Results indicate that the technique can effectively be applied to different scenarios and can generate robust solutions. Furthermore, its lower computational intensity should facilitate its application as part of a broader optimization process and thus better enable the assessment of more storage, pumping, and control alternatives.


8.2 Future Research

Previous chapters have proposed decision support tools and applied them to real or example systems. In order to further validate their applicability and begin to benchmark water use, energy, and performance metrics, future research should apply the tools to other examples and case studies. The challenges encountered in applying the tools, limitations of these approaches, and persisting questions within each chapter have also inspired potential extensions to the present research.

1. The conceptual map of water system components and their connections, presented in Chapter 2, although useful in guiding decisions does not describe the degree to which components influence each other. Future research should better characterize these connections, qualitatively and quantitatively.

2. The preparation of the data in Chapter 3, was found to be the most time consuming phase of the process, particularly because information was integrated from different sources. Future work can seek to standardize inputs and facilitate the integration of public data, in order to build ever more interoperable databases.

3. The proposed database integrated water billing, land use, and demographic information, Nevertheless, other factors can influence water consumption and inform conservation strategies. Future studies can integrate additional data (e.g., unit counts, industrial classification, participation in programs, income) in order to better understand water user segments.

4. The survey in Chapter 4 was conducted with residential water users only. Nevertheless, the characteristics and opinions of industrial, commercial, and institutional water users would likely differ and should be surveyed and compared in future research. Furthermore, results indicated that the older population was more likely to participate in
the telephone survey. Therefore, different feedback channels should also be used in the future to gain input from the different customer segments.

5. The proposed energy and performance metrics were shown to be useful indicators of energy efficiency, infrastructure performance, and costs. If applied in the future to support decision-making, they should be balanced with other considerations including costs, pressure constraints, and other social and environmental criteria.

6. Even though the performance metrics described in Chapter 6 are computed with two failure scenarios: fire flow during maximum demand, and pipe break during peak demand, for the initial assessment of the metrics, they can be applied to multiple scenarios, including simultaneous failures. Therefore future studies can analyse real networks with multiple scenarios.

7. Future research can also apply the proposed metrics and indicators, chapters 3 to 6, in designing a rating scheme for water distribution systems.

8. Chapter 7 argues that the high computational intensity of previous complex pipe sizing optimization techniques might not translate into significant savings, given the importance of other design components, such as pump and tank sizing, as well as the various uncertainties of the system. Future research should study the effects of design decisions and uncertainties on total costs, in order to better prioritize computational efforts.

9. The proposed optimization technique minimized capital, energy, and damage costs. If applied in the future to real systems, other costs would need to be included as well, such as water treatment, maintenance, and environmental damages. Furthermore, certain utility and stakeholder objectives might be difficult to valuate, but a qualitative comparison of alternatives could facilitate decision-making.

In addition to further applying the proposed tools and extending upon the present research, future research should review water distribution assumptions and rethink design objectives. The
constraints imposed by design standards and utility norms are pivotal to decision making, yet are generalized and many times based on older paradigms.
References


A.1 Collection Notice

The City of Guelph, Water Services Department is updating its Water Supply Master Plan.

Water Services, will be engaging residents to gain valuable insight on how best to manage its water resources. Personal information is being collected for a survey and will be used to further develop and optimize the Water Supply Master Plan. The survey is designed to collect the public views and opinions on community water servicing alternatives and gauge the level of satisfaction and service expectations for the Water Services Department. To ensure the public has an opportunity to provide feedback; Water Services is conducting a residential call survey. The goal of the call survey is to solicit feedback on the expectations of service, preferences in community water servicing approaches and desired community resource stewardship actions.

The call survey will begin in late January 2014. 400 households with the City of Guelph will be contacted by our partners, (market research firm to be selected by Guelph).

Results of the survey will be shared with members of the Water Supply Master Plan Update Project Team, including AECOM and the University of Toronto. These results will help the City to better understand needs and desires of the public through development of the Water Supply Master Plan Update as well as contribute to the ongoing optimization of the program. Your participation is voluntary. All individual responses will be kept confidential and will be used for further program development and optimization only.

Personal information, as defined by Section 2 of the Municipal Freedom of Information and Protection of Privacy (MFIPPA) is collected under the authority of the Municipal Act, 2001, and in accordance with the provisions of the MFIPPA.
For more information about the project please contact the Water Conservation Project Manager at:

T: 519.822.1260 ext. 2106

E: wayne.galliher@guelph.ca

For questions regarding the collection, use, and disclosure of this information please contact the Access, Privacy and Records Specialist

T 519-822-1260 x 2349

E privacy@guelph.ca

A.2 Water User Survey

Good morning/afternoon/evening my name is <si> from the research firm Oraclepoll calling on behalf of the City of Guelph. The City of Guelph, Water Services Department is updating Guelph’s Water Supply Master Plan. They are collecting input from residents on how best to manage water resources. Information from this survey will be used to develop and improve the Water Supply Master Plan. Survey questions will provide public opinion on alternatives for sourcing water for our community, and gauge satisfaction and expectations of Water Services.

Oraclepoll has been contracted by the City of Guelph to conduct this confidential 31 question, 10 minute telephone survey of 400 households in the community. Your participation is voluntary; you may withdraw at any time during the survey and may decline to answer any question. Individual responses will be kept confidential and will only be used for program development.

(Respondents are allowed to refuse to answer any of the questions in the survey. Therefore, “did not disclose” is an option for all of the following.)
## Conditions for Participating

1. Are you 18 years of age or older?
   - i. Yes
   - ii. No (exit survey, or ask for someone of age)

2. Do you get your water from the City of Guelph municipal water supply system?
   - i. Yes
   - ii. No (exit survey, thank caller for time)

## User characteristics

3. How does your household currently pay for water?
   - i. It is included in the rent or condo fees
   - ii. It is paid directly by the household (account with Guelph Hydro/Guelph Water Services)
   - iii. Don't know

4. (Only for respondents that answered “It is paid separately” in the previous question) Are you the person primarily responsible for paying your household’s water bill?
   - i. Yes
   - ii. No
   - iii. I don’t know

## User awareness

5. Do you know where Guelph’s (drinking) water comes from? If so, where is it from? (open ended question)
   - i. Eramosa/Speed River
   - ii. Guelph Lake
iii. Groundwater wells    iv. Don't know

6. If you had to estimate, how much water do you think you personally use in an average day including drinking, bathing, toilet flushing, laundry, dish washing and outdoor use? (open ended question) (adapted from RBC, 2013)

i. 1 bucket, 10 L (2.6 gal)          ii. 5 buckets, 50 L (13.2 gal)

iii. 10 buckets, 100 L (26.4 gal)    iv. 20 buckets, 200 L (52.8 gal)

v. 30 buckets, 300 L (79.3 gal)      vi. 40 buckets, 400 L (105.7 gal)

vii. Don’t know

7. Which of the following do you think is included in your water bill? Answer each separately. Yes, No, or I don’t know? (adapted from RBC, 2013)

i. Drinking water treatment

ii. The pumps and pipes that deliver water to households

iii. Wastewater pipes

iv. Wastewater treatment

v. Storm water management systems

vi. General maintenance of water systems

vii. Resource Protection and Conservation

**Concerns / Issues**

8. In your opinion, what are the most important issues facing Guelph’s water system today? Please list up to three, beginning with the most important (open
ended) (adapted from RBC, 2013)

i. Aging infrastructure  ii. Low water pressure

iii. High water pressure  iv. Environmental footprint

v. Costs  vi. Threats to water quality

vii. Leakage  viii. Scarcity

ix. Other (please specify)

9. Ten years from now, what do you think will be Guelph’s biggest water-related problem? (open ended) (adapted from RBC, 2013)

i. Water pollution

ii. Infrastructure deterioration

iii. Shortages of drinking water

iv. Flooding caused by extreme weather

v. Guelph will not be facing any water issues

vi. Other (please specify)

10. How is the City of Guelph doing in each of the following areas related to water, wastewater, and storm water systems? Answer each separately. Excellent, good, average, fair, poor, or don’t know? (adapted from RBC, 2013)

i. Providing an adequate quantity of water

ii. Providing clean water

iii. Responding effectively to repair pipe breaks
iv. Maintaining current systems

v. Upgrading systems for the long-term

vi. Ensuring that water services are priced affordably

vii. Pricing water services to cover full costs

viii. Raising public awareness about the water resource protection and conservation

11. In your opinion, how acceptable would it be for Guelph to get water from sources that require treatment to remove contaminants?

i. Highly acceptable ii. Acceptable

iii. Indifferent, Unacceptable iv. Highly unacceptable

v. No opinion

User initiative and motivation

12. How much do you personally try to conserve water? (adapted from RBC, 2013)

i. Very hard

ii. Reasonably hard

iii. A little

iv. I have already completed many actions to conserve and don’t feel I could do more.

v. Not at all
13. **(Only for respondents that did not answer “Not at all” in the previous question)** What motivates you to conserve water? Please list up to three reasons beginning with the most important *(open ended question)* *(Silva et al., 2010)*

i. I save money on my water bill.

ii. It is the right thing to do.

iii. I am concerned about water availability.

iv. I am concerned about global climate change and how it may affect water supplies.

v. I am concerned about the impact of water withdrawals on the environment.

vi. I am concerned about my family's health

vii. I changed my behavior after reading a brochure insert with my water bill.

viii. I changed my water usage after watching a television show/ad about water conservation.

ix. My neighborhood/friends are environmentally conscious, and I get pressure from neighbors to conserve water.

x. I do not know.

xi. Other (please specify)

14. **(Only for respondents that did not answer “Not at all” in question 12)** What have you done over the past two years to increase water conservation at home?
This might include reducing outdoor water use, household repairs, or purchasing water-efficient appliances. *(open ended question)* *(Silva et al., 2010)*

i. Repaired leaking faucets and/or toilets

ii. Changed lawn watering schedule

iii. Stopped watering some or all of an existing lawn

iv. Installed water-saving shower heads

v. Installed water-saving toilets or retrofitted existing toilets with water saving devices such as displacement units, early closure flappers, or fill diverters

vi. Installed water-efficient clothes washer

vii. Installed water-saving faucets or water-saving aerators on existing faucets

viii. Installed water-efficient dishwasher

ix. Planted more trees to shade the landscape and reduce evaporation

x. Purchased water-saving hose nozzles

xi. Replaced some grass with water wise plants and/or architectural features such as decks, patios, etc.

xii. Purchased soaker hoses for outside watering

xiii. Insulated hot water pipes

xiv. Installed irrigation controller with a rain sensor
xv. Checked humidifier for leaks

xvi. Replaced irrigation controller with one that contains a rain sensor

xvii. Other (please specify)

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**User Priorities**

15. In times of water scarcity, how important are the following water uses? *Answer each separately. Very important, Important, Not important, or No opinion? (adapted from Conrad et al., 2012)*

   i. Water for Municipal Operations
   
   ii. Water for Recreation
   
   iii. Water for Wildlife and the Natural Environment
   
   iv. Water for Household Indoor Use
   
   v. Water for Private Landscape Irrigation

   vi. Water for Commercial and Industrial Use

16. During a period of unavoidable, short-term water scarcity, how much would you agree with the following water management actions? *Answer each separately. Strongly agree, agree, neither agree nor disagree, disagree, strongly disagree or No opinion? (adapted from Conrad et al., 2012)*

   i. Restricting the amount of water that can be used on private lawns and landscapes

   ii. Restricting the amount of water that can be used for municipal operations
iii. Restricting the amount of water that can be used by industry and business

iv. Allowing local natural reservoirs to drain

v. Reducing the amount of water available for wildlife and fish habitats

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**Business Model - Water Supply and Rate Structure Alternatives**

17. Currently, all Guelph water customers are billed for usage by a single per cubic metre rate of $3.04 for 2014. How much do you agree with the following different water rate options? *Answer each separately. Strongly agree, agree, neither agree nor disagree, disagree, strongly disagree or No opinion? (based on rate structure types defined by US EPA, 2005)*

i. The current approach as described where all customers pay a per cubic metre rate.

ii. All customers pay the same flat fee, regardless of use.

iii. The rate per cubic meter increases as total water use increases.

iv. The rate per cubic meter decreases as total water use increases.

v. The rate varies depending on the season.

vi. Different types of customers, such as industrial, commercial, and residential, are charged different rates.

18. Guelph relies on drinking water for its water supply. Recent analysis confirms that our current water supply will not meet future needs. How much do you agree with the following strategies for additional water? *Answer each separately. Strongly agree, agree, neither agree nor disagree, disagree, strongly disagree or*
No opinion?

i. Increase our commitment to conservation

ii. Set stricter water use goals for new growth

iii. Improve our current water infrastructure

iv. Build new water infrastructure.

v. Use water from new groundwater sources within the city.

vi. Use water from new groundwater sources outside the city.

vii. Use water from Eramosa River.

viii. Use water from Speed River or Guelph Lake.

ix. Do nothing.

x. Other (please specify)

User Communication

19. How much do you agree with the following statements on communication between Guelph Water Services and customers? Answer each separately. Strongly agree, agree, neither agree nor disagree, disagree, strongly disagree or No opinion?

i. Water users are notified of changes to water servicing in their area (i.e. restrictions, local maintenance activities, changes in water rates)?

ii. Water users have the opportunity to get involved in decisions made by Guelph Water Services.
iii. My reported water issues are resolved in a timely manner.

iv. Water customers are given enough information about Guelph’s plan for providing water and their opportunities to participate in the discussion.

v. Other opinion (please specify)

20. What is the best way to reach you with information about water? *Please list up to three methods, beginning with the most effective (open ended question)* *(adapted from Silva et al., 2010)*

   i. Water bill inserts

   ii. TV ads

   iii. Newspapers ads

   iv. Radio

   v. Magazine articles

   vi. Billboards

   vii. Roadside signs

   viii. Home improvement store displays

   ix. Free home water audits

   x. Nursery or landscape company displays

   xi. Public buildings or community centers

   xii. City of Guelph website
xiii. Emailed information
xiv. Social media
xv. School or classroom discussions
xvi. Information fairs at malls or parks
xvii. Personal contact with water utility representative
xviii. Plumber consultation
xix. Public meetings or forums
xx. Local university extension services
xxi. Utility-sponsored class or conference
xxii. Irrigation contractor
xxiii. Word of mouth
xxiv. Do not want to receive any information
xxv. Don’t know
xxvi. Other (please specify)

21. How would you like to be able provide your input on Guelph’s Water Services and any proposed changes? Please list up to three methods, beginning with the most effective (open ended question)

   i. Individual customer complaints.   ii. Questionnaire surveys.
   iii. Focus groups.                 iv. Large open meetings.
Demographics

22. How many people live in your residence? Adults? Children (under the age of 18)?

23. Are you a seasonal or part time resident?
   i. Yes
   ii. No

24. Do you own or rent your residence?
   i. Own
   ii. Rent

25. How would describe your residence?
   i. Detached house
   ii. Attached house (townhouse, duplex, triplex, etc.)
   iii. Multi-family house (multiple suites in a single home)
   iv. Apartment/condominium
   v. Mobile Home

26. Which of the following age categories describes you?
   i. Under 20
   ii. 20 to 24
   iii. 25 to 34
   iv. 35 to 44
   v. 45 to 54
   vi. 55 to 64
   vii. 65 or over
27. What is the highest level of education you have completed?

i. Less than high school

ii. High school

iii. Trades or non-university certificate or diploma

iv. University

v. Post graduate degree

28. Which one of the following best describes your current employment status?

i. Student

ii. Professional/worker in an environmental related sector

iii. Professional/worker in other sector

iv. Retired

v. Unemployed

29. Which of the following categories best describes your pre-tax annual household income?

i. Below $25,000

ii. Between $25,000 and $50,000

iii. Between $50,000 and $100,000

iv. Above $100,000

30. What is your gender?
i. Male       ii. Female

Results of the survey, excluding personally identifiable information, will be shared with members of the Water Supply Master Plan Project Team, including AECOM (“eh-com”) and the University of Toronto. A summary of results will be shared on guelph.ca.

For questions regarding the collection, use, and disclosure of this information please contact the City of Guelph Access, Privacy and Records Specialist at 519-822-1260 x 2349 or privacy@guelph.ca. For more information about the project please contact the City’s Water Conservation Project Manager at: 519.822.1260 ext. 2106