DEVELOPMENT OF A MULTI-CRITERIA DECISION-MAKING FRAMEWORK FOR THE IMPLEMENTATION OF STORMWATER REUSE IN CANADIAN MUNICIPALITIES

by

Dalia Al-Ali

A thesis submitted to the Department of Civil Engineering
In conformity with the requirements for
the degree of Master of Applied Science

Queen’s University
Kingston, Ontario, Canada
(December, 2015)

Abstract

Water reuse is an increasingly popular consideration for municipalities, developers, and businesses. Currently, the majority of water reuse applications originate from Australia, Southeast Asian nations, and the Middle East. Stresses posed by population growth and/or water scarcity are the primary drivers for the prevalence of reuse applications in these regions. However, an increasing number of regions in North America are in the process of implementing, or have already implemented, some form of water reuse. Water reuse is increasingly adopted by municipalities due to its potential to combat (a) increasing water scarcity in urban areas, (b) decreasing water quality of receiving waters due to wastewater discharge and urban runoff inputs, and (c) diffuse pollution inputs from rural areas within municipalities.

This thesis focuses on stormwater reuse. In this case, stormwater is defined as runoff generated in urban areas from pervious and impervious surfaces following a precipitation event. Historically, stormwater has been regarded as an inconvenience. Traditional stormwater management efforts have primarily focused on channeling stormwater away from urban centres as efficiently as possible. However, the adverse impacts of urban runoff on receiving waters, as well as the increasing need for more intelligent water resources management, are gradually changing the perspective on stormwater. Increasingly, stormwater is being regarded as an asset rather than an inconvenience, as well as a potential alternative water source which could be used to supplement domestic water supplies.

This thesis presents the results of the research undertaken to develop a decision-making framework to aid Canadian municipalities in the planning and implementation of stormwater reuse. The objective of the framework is to provide planners, developers, and engineers with a management model to aid in understanding the interactions among the decision-making variables in stormwater reuse.

The thesis begins with a literature review covering the history of reuse in North America, with the objective of defining past and current challenges, gaps in current research, and steps necessary for more robust reuse applications. Next, a critical assessment of the reviewed literature is used to develop a decision-making framework for stormwater reuse implementation within Canadian municipalities. The framework delineates the major decision-making factors potentially influencing implementation choices, as well as the interactions among these factors. Finally, the thesis provides an example of framework application, discussion of potential framework limitations, and recommendations for future work.

Co-Authorship

Dalia Al-Ali is the primary author of this thesis. Dr. Yves Filion contributed intellectual supervision and editorial comment for all chapters.

Acknowledgements

The completion of this thesis would not have been possible without the support of a number of individuals. First and foremost, I would like to thank my parents Basim and Ektefaa for their constant encouragement and unwavering support. I am deeply grateful for my friends and colleagues in the graduate department for the laughs and inspirational conversations. And a sincere thank you to Spencer for accompanying me through the ups and downs of the past two years.

Finally, I would like to thank my graduate supervisor Dr. Yves Filion for his guidance and support throughout the course of this graduate degree.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

Water scarcity is the discrepancy between the availability and demand for water resources. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) states that water scarcity is increasingly being regarded as a major challenge for many regions internationally, and estimates that it affects one third of the global population (UNESCO, 2009). In North America, it is anticipated that increasing populations, more intensive land use, and poor watershed management will only further water scarcity concerns. The quantity and quality of fresh water resources will only be diminished unless specific water management practices are adopted (Zimmerman et al., 2008). Managing water scarcity impacts has historically involved the implementation of one or more of the following practices: water conservation, desalination, and water reuse (Nasiri et al., 2013). Water reuse is increasingly considered by municipalities due to its potential to combat (a) increasing water scarcity in urban areas, (b) decreasing water quality of receiving waters due to inputs from wastewater discharge and urban runoff, and (c) diffuse pollution inputs from rural areas within municipalities.

1.2 Overview of Stormwater Reuse and the Need for a Reuse Decision-Making Framework

Achieving ecologically sustainable growth in urban regions is critically dependent upon the establishment of sustainable water systems and the protection of freshwater resource quality and quantity (Wu et al., 2012). The sustainable management of stormwater in urban areas requires the implementation of strategies at multiple decision-making levels. However, whether local or regional, any scale of decision-making requires reliable data, comprehension of the available options and their consequences, and realistic problem definition (Barbosa et al., 2012).

For the purposes of this thesis, stormwater is defined as runoff generated in urban areas from pervious and impervious surfaces following a precipitation event (Wu et al., 2012). Stormwater management aims to minimize the negative impacts of urban runoff on receiving waters. Urbanization involves the modification of land through vegetation removal and the increase in impervious surfaces. This leads to increased stormwater runoff volumes, as well as higher peak flow generation from storm events. In addition to changes in land use, the generation of pollutants on surfaces in urban areas further impacts receiving waters as these pollutants may be transported by runoff to water bodies during storm events (Barbosa et al., 2012). The specific impacts of urban-source stormwater runoff on water bodies depend on two main factors: (1) runoff characteristics, primarily quality, volume, and flow velocity, and (2) receiving water body characteristics, primarily quality, volume, and assimilation capacity (Barbosa et al., 2012).

Historically, stormwater has been viewed as a nuisance. Traditional stormwater management efforts have primarily focused on channeling stormwater away from urban centres as efficiently as possible. However, the aforementioned impacts of urban runoff on receiving waters, as well as the increasing need for more sustainable water resources management, are gradually changing the perspective on stormwater. Increasingly, stormwater is being regarded as a resource rather than a nuisance (McArdle et al., 2011), as well as a potential alternative water source which could be used to supplement domestic water supplies (Wu et al., 2012). Mitchell et al. (2007) note that stormwater management objectives have expanded over the past thirty years, shifting from strictly flood protection priorities to incorporating ecological restoration, pollution minimization, and the improvement of stormwater value as a resource.

Approximately 50% to 80% of urban water use does not need to be treated to potable quality (Wu et al., 2012). As a result, the potential replacement of some water used in urban areas with water of lower quality (i.e. service water) is a growing area of research. An important part of sustainable urban growth is investigating the potential use of recycled stormwater to meet non-potable end uses, thus decreasing the pressure on water supplies and distribution systems by providing an alternative water source. The two primary benefits of stormwater reuse are its ability to yield an alternative water supply for urban areas, as well as its potential to improve the health of urban streams through hydrologic flow restoration (Mitchell et al., 2007).

Although stormwater reuse is a growing field of research, documentation of implemented stormwater reuse projects is still scarce. Guidance regarding the planning and implementation of stormwater reuse is sparse, and what little guidance exists often contains gaps by focusing only on specific aspects of reuse (e.g. economics of reuse; technical reuse components). Also, minimal legislative guidance on stormwater management and reuse, with gaps between federal, provincial, and municipal legislation, makes it difficult for municipalities considering reuse to determine the requirements throughout the planning and implementation of stormwater reuse projects. Currently, the disjointed guidance on stormwater reuse poses a hurdle to municipal adoption of reuse. Often, the limited budgets available to Canadian municipalities restrict their ability to invest the time and resources into investigating factors which impact the planning and implementation of reuse. As a result, this thesis presents a decision-making framework to guide municipalities through the planning and implementation of stormwater reuse. The framework presents municipalities with the pertinent factors which must be considered in a reuse project. It also ensures that they conduct a holistic assessment of factors that have an impact on implementation, with information provided regarding technical, physiographic, climatic, legislative, social, and economic decision-making factors.

1.3 Thesis Objectives and Scope

The objective of this thesis is to present a preliminary decision-making framework to aid municipalities in the planning and implementation of stormwater reuse. The framework provides planners, developers, and engineers with a management model to aid in defining the variables involved in reuse decision-making and understanding the interactions among those variables.

The decision-making framework is comprised of a two-part process. The first part outlines the overall decision-making path which a municipality must undertake upon choosing to implement stormwater reuse. This part also defines the overall process inputs (decision-making factors) and outputs (reuse system component design). The second part details the specific decision-making factors that have an impact on stormwater reuse implementation, including the sub-factors which must be investigated by the municipality and the relationships among these sub-factors. The four decision-making factors defined by the framework are: (1) technical factors; (2) physiographic and climatic factors; (3) legislative and social factors; and (4) economic factors.

It is important to note that the decision-making framework is intended to guide municipalities in the initial stages of stormwater reuse planning and implementation. The framework is not intended to dictate the specific decisions which a municipality would make; much of the data required to make concrete decisions in reuse implementation will be case-specific and cannot be wholly anticipated by the decision-making framework. Ultimately, the framework is intended to inform decision-makers about the variables involved in stormwater reuse planning and implementation and map the data requirements for reuse.

1.4 Original Thesis Contributions

The thesis research contributions are detailed below:

1. Development of a new multi-criteria decision-making framework to guide municipalities in the planning and implementation of stormwater reuse;
2. Presentation of a holistic analysis of factors impacting the planning and implementation of stormwater reuse;
3. Presentation of a novel depiction of barrier and driver relationships between decision-making factors impacting the planning and implementation of stormwater reuse;
4. Presentation of a preliminary application of the framework to a case study in southeastern Ontario and discussion of potential framework performance assessment methods.

1.5 Thesis Organization

The thesis conforms to the School of Graduate Studies thesis format guidelines. Thesis organization is described below:

Chapter 2 presents the results of an extensive literature review examining water reuse within North America from the 1970s to present day, including wastewater, stormwater, and rainwater reuse. The review first discusses the evolution of water reuse, from the focus on the technological feasibility of water reuse in the 1970s and 1980s to the emphasis on public perception studies from the millennium onwards. Next, the literature review discusses the technical aspects of water reuse systems from the 1970s onwards, primarily advances in production, distribution, and storage components. The planning and management of water reuse projects is discussed next, including economic considerations and the main implementation challenges experienced from the 1970s onwards. Finally, a summary of key current considerations in reuse implementation is presented.

Chapter 3 discusses the procedure for developing the stormwater reuse decision-making framework and presents the final configuration of the two-part framework. Following a description of the guiding principles used throughout the framework development procedure, the chapter defines the four major decision-making categories impacting reuse planning and implementation: technical factors; physiographic and climatic factors; legislative and social factors; economic factors. The next section of Chapter 3 discusses the considerations influencing framework development and presents the final decision-making methodology. A detailed description of the relationships between various decision-making variables is also presented.

Chapter 4 presents a discussion of potential framework validation methods and describes a case study involving preliminary framework application to a proposed mixed-use community in southern Ontario. Framework limitations and recommendations for future study are also discussed.

Chapter 5 outlines thesis conclusions and major research findings.

1.6 Journal and Conference Publications Related to the Thesis

Thesis contributions have been presented in the form of scientific paper submissions to peer-reviewed journals and conferences. The publications, as well as their current status, are listed below:

Al-Ali, D., Filion, Y. (2015). “A Critical Review of Water Reuse in North America: The Historical Shift from Technological Priorities to Public Perception Studies” *Proceedings of the World Environmental & Water Resources Congress, 3rd Annual Symposium on Desalination and Water Reuse – 2015*, ASCE Austin, Texas, 1173-1190.

Al-Ali, D., Filion, Y. (2015). “A Critical Review of Water Reclamation and Reuse in North America” *Journal of Environmental Management* (Submitted: November 2015).

Al-Ali, D., Filion, Y. (2015). “Development of a Multi-Category Decision-Making Framework for Stormwater Reuse Planning and Implementation” *Water Resources Management* (Submitted: November 2015).

1.7 References

Barbosa, A., Fernandes, J., & David, L. (2012). Key issues for sustainable urban stormwater management. *Water Research*, 6787-6798.

McArdle, P., Gleeson, J., Hammond, T., Heslop, E., Holden, R., & Kuczera, G. (2011). Centralised urban stormwater harvesting for potable reuse. *Water Science & Technology*, 16-24.

Mitchell, V., Deletic, A., Fletcher, T., Hatt, B., & McCarthy, D. (2007). Achieving multiple benefits from stormwater harvesting. *Water Science & Technology*, 135-144.

Nasiri, F., Savage, T., Wang, R., Barawid, N., & Zimmerman, J. (2013). A system dynamics approach for urban water reuse planning: a case study from the Great Lakes region. *Stochastic Environmental Research and Risk Assessment*, 675-691.

UNESCO (2009). World water assessment program. *The United Nations World Water Development Report 3: water in a changing world*. UNESCO, Paris and Earthscan, London.

Wu, Z., McKay, J., & Keremane, G. (2012). Issues affecting community attitudes and intended behaviours in stormwater reuse: A case study of Salisbury, South Australia. *Water*, 835-847.

Zimmerman, J., Mihelcic, J., & Smith, J. (2008). Global stressors on water quality and quantity. *Environmental Science & Technology*, 4247–4254.

Chapter 2

Literature Review: A Critical Analysis of Water Reclamation and Reuse in North America

Water reuse is an increasingly popular consideration for municipalities, developers, and businesses. Currently, the majority of water reuse applications originate from Australia, Southeast Asian nations, and the Middle East. Stresses posed by population growth and/or water scarcity seem to be the primary drivers for the prevalence of reuse applications in these regions. However, an increasing number of regions in North America are in the process of implementing or have already implemented some form of water reuse. As a result, this chapter aims to present an overview of the history and current state of reuse in North America, with the objective of defining past and current challenges, gaps in current research knowledge, and necessary steps for more robust reuse applications. The chapter critically assesses the trajectory of reuse projects in North America from the 1970s onwards, highlights the similarities and changes in reuse development, and discerns the critical hurdles to widespread implementation.

2.1 The Evolution of Water Reuse in North America

The following section presents an outline of the evolution of water reuse practices in North America. The overarching trajectory of water reuse is discussed, as well as relevant milestones and legislative frameworks.

2.1.1 The Initial Stages of Reuse (1970s to Early 1980s)

In 1980, a critical event within the field of water reclamation and reuse was the Water Reuse Symposium in Washington, D.C. The Symposium provided a snapshot of the research foci within the field at the time. Smith (1980) provided a discussion of the papers presented. Firstly, the majority of papers were focused on determining the technological feasibility of utilizing reclaimed water. Secondly, almost all municipal reuse papers discussed the use of reclaimed wastewater from centralized municipal treatment plants for various end uses. The reuse of water from other sources (e.g. stormwater runoff) was only briefly discussed. Also, decentralized reuse was not discussed.

At the Symposium, discussions of pilot studies and full-scale reuse systems were centered on the technological feasibility of wastewater reclamation and reuse. The focus on technological aspects was exemplified by Miller and Lambert (1979), who discussed that the success of wastewater reuse was primarily dependent upon achieving high treatment efficiencies. Mattock (1978) summarized the results of 26 symposium papers, all of which centred on an evaluation of new wastewater treatment technologies at the time. Gas transfer and biological treatment processes were among those presented. The design of advanced wastewater treatment plants, typically involving tertiary treatment, was a main topic of discussion. Note the predominant emphasis on municipal wastewater reuse and recovery, as opposed to other sources of water for reuse. Industrial wastewater recycling was also significant at the time due to the then newly stringent regulations limiting toxic discharges.

The 1970s and early 1980s also saw the establishment of water reuse legislation and research programs in the United States. The U.S. Environmental Protection Agency (EPA) played a role in the water reclamation and reuse area from the 1970s. They began implementing legislative changes which recognized the role of water reuse as an essential component of the EPA’s water quality management goals. In 1980, the EPA’s objective was to review all federal loan and grant frameworks relating to municipal water infrastructure. Their aim was to promote water conservation practices through the creation of new incentives. The EPA’s wastewater reuse research program is most relevant. At the time, the program investigated the reuse of wastewater in municipal, agricultural, and industrial settings (Gage, 1979).

The U.S. Office of Water Research and Technology (OWRT) also established a water reuse research initiative. The OWRT began the program under the Water Resources Research and Development Act of 1978. The research program objectives were to (1) establish reuse needs, (2) evaluate treatment options, and (3) define planning and management requirements within the reuse area (Madancy, 1979). In addition to the aforementioned research programs, the Clean Water Act of 1977 also played a role in shifting the attention of industries and municipalities towards reuse. Innovative waste management approaches such as the reuse of wastewater were allotted financial incentives by the Act (Thomas et al., 1979).

Within North America, the majority of advances in water reuse throughout the 1970s and early 80s occurred in the United States. In the U.S., California was responsible for a significant portion of the reuse case studies presented at the Water Reuse Symposium in 1980. California's institutional and legislative infrastructure for reuse was exemplary at the time and included the following activities: the Office of Water Recycling managed demonstration sites (Wassermann & Radimsky, 1979); the California Department of Health Services initiated a program to examine potential health risks associated with wastewater reclamation (Crook & Spath, 1979); and a regional water reuse plan was in development (Home & Hazel, 1979). The three research objectives of the regional reuse plan were: (1) study of health effects; (2) study of project feasibility and marketing; (3) study of institutional and economic factors that affect large-scale water reuse. These objectives were primarily aligned with present day reuse priorities.

It is important to note that while certain interests have changed in the evolution of water reuse, a notable number of concerns have not been resolved and remain from the initial stages of reuse research in North America. In 1979, Milliken and Trumbly discussed municipal wastewater reuse for domestic end-uses and concluded with a projection that by 1995 non-potable reuse will be prevalent in the U.S. This projection proved to be wrong and this is perhaps telling of the still pervasive public acceptance and legislative hurdles in the widespread adoption of reuse.

Papers presented at the Water Reuse Symposium highlighted reuse research in other regions as well. Additional reuse projects were deemed necessary in Denver, Colorado (Heaton, 1978). A discussion of water supply concerns and the potential for reuse in Phoenix, Arizona was presented (Fulton & Chase, 1979). Reuse potential and wastewater reclamation plans were presented for Chicago (Lake Michigan area), Virginia, and Florida.

2.1.2 Reuse from the Late 1980s to 2000

By 1985 industrial and agricultural reuse of wastewater continued to grow and, for many communities, municipal reuse was becoming a more acceptable practice (DeBoer & Linstedt, 1985). However, the disparity in the acceptance of low- versus high-level reuse was still prominent. Low-level reuse includes end uses such as landscape irrigation, while high-level reuse involves more intensive treatment to achieve potable end uses. Although both types of reuse were discussed for urban settings at the time, each had very distinct challenges and public acceptance issues. Reuse of water for potable end uses remains predominantly undesirable in North America. Most successful and long-term municipal water reuse applications at this time involved the use of treated wastewater to meet irrigation end uses in metropolitan areas. Widespread attention to water reuse was attributed to two main factors at the time: (1) shortages in water supplies; and (2) more stringent wastewater disposal regulations (DeBoer & Linstedt, 1985).

By the late 1990s, water-scarce regions in the United States were well aware of the water reuse concept and most had well-established reuse programs. At this time, an increasing number of municipalities in North America were considering the adoption of reuse practices due to the fact that an increasing number of traditional water sources became, or were projected to become, stressed (Crook, 1998). Agricultural and landscape irrigation end uses for reclaimed water were considered widely accepted and practiced in the United States at this time. Reuse regulation was done on a state-by-state basis as no governing federal regulations existed. At the time, none of the state reuse regulations targeted all potential reuse end uses. Also, a very small number of states addressed potable reuse in their reuse regulations. The EPA Guidelines for Water Reuse published in 1992 provided planning and implementation guidance to the individual states (USEPA, 1992). This document illustrated the many challenges in the implementation of urban reuse, the most critical of which is the requirement for high treatment efficiencies. The need for high level treatment, typically yielding pathogen-free water, is due to the potential for human contact either through direct or indirect use. By 1998, the use of reclaimed water to meet toilet flushing and fire suppression end uses was prohibited for single-family residential units in the United States due to the unknown risk factors associated with potential human contact (Crook, 1998).

2.1.3 Reuse from 2000 to Present Day

The Canada Mortgage and Housing Corporation (CMHC) published guidelines on residential water reuse systems which provided an assessment of water quality monitoring procedures for these systems (Canada Mortgage and Housing Corporation, 2000). The document stated that the following specific parameters must be monitored in a residential reuse system: turbidity, colour, odour, suspended solids, and chemical/biochemical parameters (e.g. Biochemical Oxygen Demand; Dissolved Oxygen; organic compounds). The document also examined monitoring needs and reuse system reliability for residential units as a means of addressing health and safety concerns posed by homeowners and property managers. Only indirect water reuse processes, such as reuse for toilet flushing and laundry, were examined. At the time, the CMHC had several demonstration sites featuring water reuse systems in Canadian regions (Ottawa, Toronto, Vancouver, and the Far North). The document ultimately presented a monitoring protocol for indirect water reuse. Subsequently, Health Canada published national guidelines for the indirect use of domestic reclaimed water (Health Canada, 2010). The document emphasized reuse water quality and the need for proper treatment and management of domestic reclaimed water in order to protect the public from potential health risks. It defined elements of potential management and monitoring frameworks for domestic reuse, much like the aforementioned CMHC guidelines. However, the Health Canada guidelines also discussed the decentralized treatment of reclaimed domestic water. Decentralization is a concept that is garnering increasing attention in the reuse community. Unlike most published reuse literature prior to 2000, which focused on obtaining high quality effluent from central wastewater treatment plants and pumping it to customers for reuse, current reuse literature is recognizing the economic potential in decentralized reuse (Vassos, 2014). Decentralization involves the reuse of water reclaimed at a given site on that same site. Pumping and piping costs are significantly reduced, and the detection of potential reuse system malfunctions becomes a less onerous task than with centralized, municipal systems.

In addition to the growing consideration of reuse in residential settings, wastewater reclamation continues to be an important consideration for water scarce regions in North America. It was cited as a potential means of stabilizing California's water resources. As of 2011, approximately 200 billion gallons of water was being recycled annually in California (Torrice, 2011).

Pricing of reused water and the implementation of cohesive reuse policy both garnered increased consideration in the literature post-2000 (McVicar et al., 2012). The state of current reuse practices in North America was summarized by the document titled "Water Reuse in Alberta: Experiences and Impacts on Economic Growth" (WaterSMART Solutions Ltd., 2013). The purpose of this document was to investigate the water supply challenges that affect the province of Alberta. The report also provided a foundation for the development of water use and reuse policy and technologies in the province. This was done by undertaking a review of current legislation in Alberta, British Columbia, the United States, and Australia, as well as conducting interviews with individuals within Alberta. Several challenges were identified within the reuse field and will be discussed in Section 4.2. The report notes some common factors in the current state of water reuse within North America. One of these factors is that the pervasive challenge in reuse is no longer its technical aspects or the lack of political support behind the idea of reuse; the major challenge now is the development of a tangible legislative framework which would permit water reuse to move from a conceptual to an applied state in many regions. The technological innovation for reuse is available and water conservation needs are at the forefront. However, the practical legislative and management frameworks for implementation are lacking. Also, the wide degree of variation among existing reuse legislation in North America makes reuse implementation a difficult task for municipalities, city planners, and property managers and developers. Public acceptance and the intricacies of public consultation and project transparency were also cited as common hurdles for reuse implementation.

2.2 Water Reuse Systems: Production, Distribution, and Storage

In the 1970s and early 1980s, research on water reuse systems was focused on the verification of tertiary treatment technologies and the monitoring of reuse water quality. Williams and Faisst (1979) evaluated the efficiency of treatment systems for domestic reuse. It was noted that local conditions must be assessed in the development of reuse programs. A small-scale treatment system for cold-climate regions was described by Bromley and Benedek (1979). The system was capable of yielding effluent quality which made non-potable reuse possible. The treatment train consisted of extended aeration, adsorption, and chlorine disinfection chambers.

The U.S. Army and Air Force wastewater reuse systems at the time were mobile, modular, and tailored to field use. Known as an "environmental service module", one such system was comprised of a train of advanced treatment modules aimed at yielding recycled water (Smith & Laughton, 1979). Another system designed for army medical facilities was designed to meet multipurpose needs; it could yield non-potable water for reuse from greywater and potable water from natural sources (Lee & Reuter, 1979).

By 1985, the most common municipal reuse application involved the use of treated wastewater to meet irrigation demands in urban areas (DeBoer & Linstedt, 1985). Technical treatment requirements for these applications varied slightly depending on the specific irrigation end use (e.g. a public park versus a golf course). At the time, irrigation reuse applications in Colorado Springs, Colorado and Tucson, Arizona utilized dual-media pressure filters to further treat chlorinated secondary effluent from municipal treatment plants prior to reuse (Smith & Guild, 1984) (Cafaro et al., 1984). The final treated product was deemed acceptable for golf course and parks irrigation purposes.

The proper design and operation of distribution systems is critical to the protection of reuse water quality and meeting user demands. Distribution system integrity is a key aspect in the water reuse operation. Implementing municipal irrigation reuse projects was facilitated by the installation of dual distribution systems. These systems transport reclaimed water and potable water to a given customer area. Key system components include pipe distribution network, pump stations, and storage tanks where necessary (DeBoer & Linstedt, 1985). For a customer area that receives water from a dual distribution system, the potable supply pipe typically requires the installation of a backflow prevention device. In the event of accidental cross-connections in the dual distribution system, the backflow preventer would minimize the potential for drinking water system contamination. Note that the potential for cross-connections in a dual distribution system was cited as the main reason that reclaimed water used to meet toilet flushing end uses was required to be treated to almost pathogen-free standards. Despite the fact that the potential for human contact is very low in this case, the high treatment requirements were implemented to reduce health risks in the event of cross-connections to drinking water systems (Crook, 1998). As mentioned, distribution system integrity is critical in the successful implementation of reuse projects.

The reliability of treatment methods is a critical aspect of reuse. Although the efficiencies of specific treatment processes will not be covered in this chapter, it is important to note that a large portion of the reuse literature is dedicated to the testing and verification of reclaimed water quality using different treatment sequences. Typically, reclaimed water quality standards are set for the following parameters: biochemical oxygen demand (BOD); total suspended solids (TSS); total/fecal coliform bacteria; turbidity; nitrogen; chlorine contact duration and residual concentration (Crook, 1998).

In terms of reuse water storage, Crook (1998) discussed the disadvantages of open storage systems, stating that the reclaimed water quality would be undermined by algae and microorganism activity, particulate matter intrusion, and odor/colour issues. All the aforementioned quality issues may be minimized by using a closed storage system; above ground enclosed storage tanks or underground storage tanks have both shown success in reuse projects throughout the last few decades.

For rainwater and stormwater reuse, the following primary system components are required: (1) an impervious surface to collect the stormwater/rainwater (e.g. paved parking lot; house roof); (2) a storage tank to hold the collected water; (3) a means of distributing water to end users (Boulware, 2013). Quality of reused stormwater or rainwater is dependent on the state of the collection surface and storage tank performance in terms of pathogen reduction or increase. Stormwater is considered to be of lower quality than rainwater due to the fact that it is collected from urban surfaces such as sidewalks and roads, which are generally more polluted than rooftops. It is important to note that the construction materials in these reuse systems play an important role in quality control; roofs, gutters, pipes, and storage tanks must be made of inert materials (Boulware, 2013).

2.3 Planning and Management in Water Reuse Projects

The following subsections highlight reuse water sources and end uses, design considerations, reuse economics, and potential barriers as discussed in the reuse literature from the 1970s onwards.

2.3.1 Design Aspects and Guidelines

2.3.1.1 Water Reuse Planning: Sources and End Uses

Specific reclaimed water treatment methods and their performance metrics are not covered in this chapter. However, water quality criteria must be developed for each reuse project. These criteria are typically based on the following considerations (Crook, 1998):

- ***Public health:*** Most reuse regulations are centred on the protection of human health. As a result, reclaimed water must be treated such that it is safe for its anticipated use.
- ***Environmental factors:*** The ecological health of receiving waters and other areas impacted by reclaimed water use (e.g. public parks) must be protected.
- ***End use objectives:*** Depending on the reuse application, specific chemical and physical water quality objectives may be required (excluding public health and environmental objectives).
- ***Irrigation impacts:*** Reclaimed water impacts on crops, soils, surface water, and groundwater must be assessed for irrigation end uses.
- ***Political variables:*** Water reclamation and reuse regulations are affected by technical feasibility, economics, and public policy. As a result, the implementation of reuse projects is affected by the standards set in legislation which, unlike deadline-driven projects, do not necessarily place cost-effectiveness as a top priority.
- ***Aesthetics:*** Reclaimed water should be clear, odourless, and colourless and should not stimulate algae growth.

The different types of potential end uses for reuse water were discussed by Milliken and Trumbly (1979). The main types of end uses proposed at the time were as follows: potable; non-potable (also known as dual distribution); agricultural; and industrial. Multiple functions were met by reclaimed water in Lubbock, Texas, including irrigation of crops and recreational uses such as providing water for decorative fountains (Bertram, 1978). The potential for recycled greywater to meet domestic irrigation needs was discussed by Brown (1979). It is important to note that in the 1970s and early 1980s, a large portion of the literature on reuse was dedicated to investigating the potential for reuse to meet agricultural/irrigation end uses. Potential water quality issues, crop effects, groundwater impacts through seepage, nutrient accumulation, and the impact on irrigation systems were investigated. It is possible that these priorities were dictated by the fact that, within the United States, agriculture comprised over 80% of the water demand in 1965 (Weinberger, 1978).

A feasibility study in Phoenix, Arizona examined the potential reuse of municipal wastewater to meet irrigation end uses (Nelson & Cox, 1979). The assessment involved an evaluation of the following factors: hydrological, institutional, legal, and economic. The planning of reuse activities by the East Bay Municipal Utility District in California was detailed by Larkin (1979). A significant portion of the planning effort was the determination of potential customer locations and water requirements for non-potable uses.

A successful water reclamation and reuse project in the San Francisco Bay area was discussed by Hermanowicz et al. (2001). The project involved the construction of a wastewater reclamation plant and a secondary distribution system for supplying the reclaimed water to meet landscape irrigation needs. A critical element during the design phase was demand analysis for the areas receiving the water for reuse. The success of the project was attributed to early customer contact and collaboration with the local water agency. The water district began by identifying the number of potential customers. Then, they estimated the potential water demand (volume per time), began drafting design plans, and submitted the required regulatory approvals. All these steps are critical in the planning and implementation of reuse projects. Additionally, in an urban environment, reuse water typically functions to replace the potable water supply in one or more end uses. As a result, the authors noted the requirement for careful consultation with the municipal water utility due to the fact that it would experience a loss of revenue. Note that at the time, the state of California imposed water quality controls on BOD, pH, coliforms, turbidity, and minimum chlorine residual. The authors noted that these controls are technologically achievable, and the significant challenges were of a non-technical nature (e.g. institutional; public perception; regulatory; financial).

2.3.1.2 Primary Economic Considerations in Reuse Projects

Economic parameters that affect the reuse of wastewater were presented by Milliman (1978). Four critical parameters were defined: (1) creation of regional water management systems; (2) implementation of unified investment management, pricing, and operating choices in urban areas; (3) charging users on a marginal cost basis; and (4) relying on cost-benefit analyses to dictate water resources investments and environmental management.

Costing and design of municipal reuse projects may be complicated by factors such as seasonal return flow variation, changes in reuse water requirements (quantity-based), contaminant accumulation, and energy prices (Milliken & Trumbly, 1979). In a study of wastewater reclamation and reuse potential in the San Francisco Bay area, Harnett and Hall (1979) reported that if reclaimed water prices were competitive with other water sources, then the potential market for reclaimed water would be too large to satisfy based on their projections.

The financing of municipal reuse systems was discussed for case studies in Colorado Springs, Colorado. An assessment determined that the following financing alternatives were available at the time: (1) using already existing financial reserves; (2) debt financing; (3) charges placed on system development; (4) subsidy from alternative city funds; and (5) a combination of two or more alternatives (Cafaro et al., 1984). The authors emphasized that the chosen financing strategy will depend upon the specific case within a given community.

Studies on the impacts of reuse water on the overall water system economics were, and continue to be, a major discussion topic in the reuse community. Revenues associated with the water system will be influenced by reuse water charges, which are typically lower than those associated with potable water. The price difference between reclaimed and potable water will depend on the specific reuse case. Although the lower reuse prices are beneficial in generating a consumer base, they have an adverse impact on revenues associated with municipal water supplies (DeBoer & Linstedt, 1985).

McVicar et al. (2012) noted that a particular challenge in the pricing of reclaimed water is that its viability is often evaluated from a traditional economic basis. In other words, there is no established means of valuing the internal versus external benefits of reuse, which could better highlight the more implicit advantages of reuse (e.g. environmental benefits).

Molinos-Senante et al. (2013) stated that the primary difficulty in establishing water reuse policy is that the achievement of the following three economic factors is not simultaneously possible: (1) pricing for the management of water demand; (2) pricing for promoting increased usage of reclaimed water; and (3) pricing for project cost recovery. The American Water Works Association (2008) defined only five projects within the United States which managed to price reclaimed water at 75-100% of drinking water rates. Pricing for water reuse in the United States is impacted by several factors. Approximately 42% of water utilities in the U.S. emphasize that it is less important for them to recover full reclamation costs than to encourage water reuse. Other utilities conduct market analysis or use a predetermined percentage of drinking water rates to set the price of reuse water (AWWA, 2008).

2.3.2 Implementation Considerations and Challenges

In the 1970s and early 1980s, the challenges in reuse implementation were not significantly different from current challenges. The institutional barriers in the reclamation and reuse of wastewater were noted for three different projects within California. The most dominant area of concern was defined as potential public health risks. The economics and pricing of reclaimed water was another critical area of concern. The institutional and legal frameworks within which water reuse is managed were also discussed. Milliken et al. (1979) also examined legal and institutional challenges in water reuse planning. The authors used five projects in the Colorado River basin to illustrate these challenges. The State-specific allocation of water was defined to be an important factor in supporting reuse projects. Also in the Colorado River basin, Lohman (1979) highlighted political tensions associated with reuse projects in the planning stage, mainly relating to conflicting homeowner preferences in relation to land use and space availability in the basin. Ultimately, no compromise could be reached in bringing the highly contradictory priorities of the stakeholders involved. Lohman also discussed the complexity in defining the institutions and stakeholders involved in water resource management and the fact that many of the barriers in reuse implementation are either created or removed by the individuals involved in the decision making process. The paper emphasized the role of public acceptance in reuse adoption – a barrier which continues to be prevalent in current reuse efforts.

Other authors also highlighted hurdles in public acceptance. Sims and Baumann (1978) surveyed health officials and public works engineers and noted that greater acceptance was linked to increased dissociation with reclaimed water. At the time, the authors found that public acceptance was 96% for non-potable end uses such as irrigation. Acceptance was significantly lower (48%) for potable/drinking end uses. The authors concluded that knowledge of reuse seemed to play a significant role in public acceptance, while the price of reuse water did not seem to have as much of an impact on acceptance. Two communities in California were used to assess public opinion on reuse: one with active involvement in reuse projects and one with no involvement (Olson et al., 1979). The authors found that public acceptance was affected by the following factors: degree of formal education (increased education resulted in increased acceptance); area of specialization; and perceived economic advantages. They also stated that both communities found a wide range of “low-order reuse activities” acceptable.

Health effects, perceived and real, have been a constant challenge in water reuse adoption. Even now, defining the actual health effects associated with different reuse practices continues to be a difficult task. In 1979, Cogley et al. (1979) presented a list of policy recommendations which take into account the potential health effects of reuse water for shower and laundry end uses. Isaacscon (1979) stressed the need for epidemiological studies in the determination of health impacts of reclaimed water usage.

At the time, much of the published literature on reuse health effects was focused on determining appropriate quality testing methods for detecting the composition of tertiary-treated wastewater; determining a test with a detection range that is suited for the residual contaminant levels was a larger challenge then than it is now.

Direct water reuse (i.e. for potable purposes) and barriers to its implementation were discussed by Huang (1979), who stated that direct reuse is feasible technologically speaking but, even at the time, the “psychological obstacle” to the concept was cited as a hurdle to its widespread adoption in the United States. Papers published in the past decade or so have begun to tackle and try to understand the intricacies of the psychological challenges to acceptance.

Although studies on reuse acceptance are currently far more targeted than in previous decades, the technological challenges in water reuse continue to be a hurdle for widespread implementation (Torrice, 2011). However, the nature of the technological challenges has changed; reuse literature in the 1970s, 1980s, and 1990s focused on the verification of performance efficiencies for the then-emerging tertiary treatment technologies, while current literature is concerned with the detection and removal of emerging contaminants from reclaimed water. Note that this statement is specific to wastewater reuse. Rainwater and stormwater reuse is less established than wastewater reuse in North America. This may be due to the fact that the main proponents of reuse in the 1970s and 1980s were states which were experiencing or forecasting water supply shortages due to their aridity, thus making rain- or stormwater reuse an impractical option.

Torrice (2011) summarized an important project in targeting public acceptance and management issues that affect water reuse in California. The project was conducted by Luthy and Bischel, who developed a survey for water agency managers with the help of social scientists. The survey included questions about reuse projects implemented by the water agencies, including inquiries into the specific end uses for the reclaimed water as well as challenges encountered by the agencies during the planning and development phases of these projects. The following paragraph highlights key findings from this study.

A total of 134 water agencies were contacted by Luthy and Bischel, and 71 agencies responded to the survey. Approximately 90% of responses cited money-related challenges as a key issue. These challenges included capital costs for the treatment components of the system, pipeline construction costs, and determination of funding sources for the reclaimed water. Some agencies countered the funding issues by searching for means to spread out costs, thus preventing reused water prices from becoming excessively high. The authors note the energy-intensive nature of the water reclamation process from wastewater treatment facilities. They stress the importance of developing technologies which would help make the treatment process more energy neutral. Following cost-related issues, the next major challenge was the management of public perception of reclaimed water. The agency managers stated that this challenge may be alleviated by working with the communities to ensure that (1) individuals understand the way the reuse system functions, and (2) project transparency is maintained throughout the duration of development. Gaining and maintaining customer trust is paramount to the smooth implementation of reuse projects. Luthy emphasizes the importance of explaining the need for reuse to, and openly discussing potential project issues with, receiving communities (Torrice, 2011).

In the 1990s, reclaimed water quality monitoring was one of the main challenges in the development of reuse regulations and guidelines. Monitoring criteria include the determination of water quality parameters to measure, numerical range of detection, frequency of sampling, and compliance limits (Crook, 1998).

The Canada Mortgage and Housing Corporation guidelines on residential water reuse systems identified two main barriers to the widespread adoption of reuse technology in Canada: (1) lack of definitive data on reclaimed water quality; and (2) lack of a legislative framework for reclaimed water monitoring requirements (Canada Mortgage and Housing Corporation, 2000).

A report on water management and reuse in Alberta identified the following challenges currently impeding reuse implementation in the province:

- “Water supply challenges – resulting from increasing water demand, water governance restrictions, and allocation system provisions – are limiting community development and economic growth;

- Water policy and legislation does not provide a clear definition of water reuse or its sources, thus creating confusion over who has the rights to reused water – the province or the license holder;
- The current regulatory framework is trailing behind the interest of communities to develop water reuse projects, thus hampering innovative solutions to water challenges;
- Alberta appears to be lagging behind other jurisdictions in Canada and around the world in providing a legislative framework to support water reuse;
- Each land use region has unique water challenges and potential reuse opportunities;
- The relationship between water reuse and return flows is not well understood." (WaterSMART Solutions Ltd., 2013)

The above challenges are far from unique to the province of Alberta and are common to many regions in North America. It is difficult to ascertain the cause-and-effect relationships between these current challenges. For example, the lack of legislative framework within a province or state may be due to the difficulty in creating blanket regulations for a site-specific practice such as reuse. It may also be attributed to the lack of resources in a given region to create robust reuse regulations and enforce them. Several other factors may also be at play in this case. The complexity of the connections linking technology, policy, public perception, and economic factors in the water reuse field continue to challenge the practical adoption of reuse.

2.4 Primary Considerations in Current Water Reuse Projects

The development of a coherent decision-making framework for the implementation of stormwater reuse in municipalities is complicated by the fact that stormwater reuse is inherently dependent upon an interaction between urban and environmental systems. Letcher et al. (2006) highlight the characteristics common to environmental systems. Firstly, environmental systems commonly contain nonlinear interactions between various system components (e.g. physical; biological; social). As a result, models depicting these systems must often rely upon assumptions which simplify the complex relationships between the variables involved. Secondly, components within environmental systems display a wide degree of heterogeneity; spatial and temporal variations between system components make these systems difficult to model accurately. Thus, decisions must often be made as to which system components and processes to include in environmental models and which to exclude. Finally, certain components of environmental systems cannot be directly observed and, as a result, knowledge regarding these components/processes is limited.

Stormwater is a single component (or subsystem) of the wider environmental system depicted by the hydrological cycle of a given watershed. Thus, prior to developing the reuse framework, it is necessary to present a discussion of factors impacting current water reuse projects. The following subsection summarizes these factors.

Stormwater and rainwater reuse provide municipalities with a sustainable option for development. The localized collection of stormwater or rainwater deposited on a specific site, then retaining and reusing this water to meet site-specific demands can, with increased municipal implementation, play a significant role in the conservation of water resources (Kinkade-Levario, 2007).

The successful implementation of a stormwater reuse system requires the consideration of the following site-specific factors: (1) catchment area selection and characteristics; (2) anticipated stormwater quantity; (3) stormwater quality; and (4) geophysical traits associated with the location of interest. These site-specific factors will greatly influence the design and implementation process of each reuse system component, including the collection, treatment, storage, and distribution system. As a result, prior to system implementation, it is necessary to ensure that (a) local stormwater behaviour is researched and characterized, and (b) pertinent local traits, such as topography and hydrology, are researched and characterized. This information plays a significant role in determining the feasibility of reuse adoption in the first place. For example, determining the quantity of stormwater which can be collected (based on catchment size and land availability) and comparing that quantity with anticipated site-level demand for various end-uses (e.g. irrigation; toilet flushing) can provide a rapid assessment of reuse feasibility (Kinkade-Levario, 2007). It is important to note that the majority of current water reuse projects are designed to meet non-potable demands only, with some projects involving reuse for aquifer (groundwater) recharge which can then be extracted and treated for potable use (a.k.a. indirect potable reuse) (Asano, 2007). Only reclaimed wastewater has been utilized for groundwater recharge projects thus far. However, commercial, industrial, and non-potable water demands comprise the highest water use fractions in urban regions so non-potable reuse has the potential to play a significant role in water conservation efforts (Asano, 2007).

Finally, a crucial site-specific consideration is the integration of a given water reuse project within the overall water resources management scheme in the municipality (Asano, 2007). Water reuse implementation cannot occur in isolation from existing and planned municipal water infrastructure.

Stormwater reuse implementation requires the consideration of a complex set of social aspects. Successful implementation necessitates the cooperation of multiple governmental departments (drainage works; planning; etc.) and public engagement programs (Barbosa et al., 2012). However, due to the limited number of documented stormwater reuse projects with detailed assessment of the social factors involved, municipalities often have no guidance on the social aspects associated with reuse implementation nor the social/institutional barriers they may encounter.

Public acceptance of water reuse continues to be a hurdle for municipal implementation of reuse. The technology available to treat reclaimed (from wastewater) and harvested (from rainwater/stormwater) water to acceptable quality for reuse is now available. However, the limited number of documented applications of reuse projects – especially stormwater reuse – and the lack of established guidelines and public policy relating to reuse in many North American regions are main factors in the reluctance of municipalities to adopt reuse projects. There continues to be a need to determine the specific health and safety risks which may be associated with water reuse (Asano, 2007).

Urgency has proven to be a significant motivating factor for the implementation of water reuse projects in recent years; urgent societal water needs in the face of existing or imminent water shortages has driven the adoption of successful water reuse initiatives (Asano, 2007). Efforts relating to the strategic planning and implementation of reuse projects to meet long-term water demands are less common.

Legislation plays a critical role in bridging the scientific research and knowledge on water reuse with the application of reuse projects. Currently, the disjointed nature of legislation relating to water reuse in many municipalities presents a hurdle for reuse implementation. A prevalent challenge in the establishment of water reuse legislation is the lack of guidance on the incorporation of uncertainty in policy (Asano, 2007).

In recent years, there has been increased research and application of decentralized (site-level) water reuse systems. From an economic standpoint, decentralized reuse eliminates the need for large construction and infrastructure retrofit investments and is typically a more cost-efficient option. A current economic hurdle to the adoption of water reuse is that, although its adoption has the potential to be cost-effective in the long term, an initial capital investment must be made to implement the collection, storage, treatment, and distribution infrastructure required (Asano, 2007).

Ultimately, the adoption of stormwater reuse projects by municipalities is currently hindered by the presence of multiple related variables whose nature and interactions have not been delineated by pre-existing reuse projects. As a result, the level of risk associated with stormwater reuse implementation remains too significant for most municipalities to realistically consider its adoption.

2.5 Integrated Planning and Management of Water Resources

Integrated water resources planning and management is defined as the strategic management and development of water resources, with the aim of achieving sustainable resource utilization while maximizing social and economic benefit (Asano, 2007). Integrated management often requires the consideration of multiple environmental compartments which may be impacted by water-related management decisions (e.g. land/soil impacts; ecological impacts). The adoption of integrated planning and management in water reuse projects is limited by the lack of guidance or methodology on multi-compartment, multi-criteria decision-making. There is a limited amount of data available on competing priorities in reuse decision-making and achieving sustainable and equitable water use from a social and ecological standpoint (Asano, 2007).

2.6 Summary

The incorporation of water reuse projects into existing drinking water and wastewater infrastructure involves the consideration of technological, social, economic, and environmental parameters, making the decision making process a challenging one. In addition to these parameters, the successful implementation of reuse must consider regional and climatic factors at the project location (Nasiri et al., 2013). Despite the multiple variables involved, water reuse is increasingly becoming a necessary consideration for regions with projected or current water scarcity issues. Water reuse in North America has seen many changes since the 1970s. It was first primarily implemented by states with water scarcity problems but has since seen an expansion into other states and provinces. Technological challenges dominated the reuse field in the 1970s and 80s. However, public acceptance and the development of legislative frameworks for reuse are the more prevalent present day challenges.

The presence of several decision-making factors in reuse projects with poorly understood relationships often causes municipalities to be reluctant in adopting these projects. The framework presented by this thesis aims to present a succinct depiction of the major decision-making factors involved in reuse implementation, as well as the primary relationships between said factors, and thus serve as one tool for the task of risk management by municipalities.

2.7 References

Asano, T. (2007). Water reuse: Issues, technologies, and applications. McGraw-Hill.

AWWA (2008). *Water reuse rates and charges: survey results*. American Water Works Association, Denver, Colorado.

Barbosa, A., Fernandes, J., & David, L. (2012). Key issues for sustainable urban stormwater management. *Water Research*, p.6787-6798.

Bertram, J. (1978). *Water Reuse in Agriculture, Industry, and Recreation*. In "Planning for Water Reuse" D. D. Baumann and D. M. Dworkin, Maaroufa Press, Inc., Chicago, p.121.

Boulware, E. (2013). *Alternative Water Sources and Wastewater Management.* McGraw-Hill Professional.

Bromley, D., & Benedek, A. (1979). Reduction of Potable Water Demand in the Arctic by Reuse. *Proc. Water Reuse Symp., Vol. 2*. AWWA Research Foundation, Denver, Colorado.

Brown, N. (1979). Sewage and Organic Waste Irrigation. Vol. 2: July 1977-July 1979 (Citations from NTIS Data Base). NTIS No. PS-79/1046, 79, 25.

Cafaro, D., Wilson, D., & Aasheim, S. (1984). Short range non-potable water management plan: Colorado Springs, Colorado. *Presented at Water Reuse Symposium 3*, San Diego, California.

Canada Mortgage and Housing Corporation. (2000). *Water Quality Guideline and Water Monitoring Tools for Residential Water Reuse Systems.* Retrieved June 2014, from https://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/99115.htm

Cogley, D., Foy, W., Light, W., Mason, M., & Eaton Jr., J. (1979). Evaluation of Health Effects Data on the Reuse of Shower and Laundry Waters by Field Army Units. *Proc. Water Reuse Symp., Vol. 3*. AWWA Research Foundation, Denver, Colorado.

Crook, J., & Spath, D. (1979). Wastewater Reclamation in California. *Proc. Water Reuse Symp., Vol. 3*. AWWA Research Foundation, Denver, Colorado.

Crook, J. (1998). Water Reclamation and Reuse Criteria. In R. Surampalli, & K. Tyagi, *Advances in Water and Wastewater Treatment* (pp. 303-329). American Society of Civil Engineers.

DeBoer, J., & Linstedt, K. (1985). Advances in water reuse applications. *Water Resources*, 1455-1461.

Fulton, J., & Chase, W. (1979). Waste Water Reuse in Phoenix - How Viable Is It?. *Water Resources Bulletin*, 15, p.426.

Gage, S. (1979). The Environmental Protection Agency's Research Program for Water Reuse. *Proc. Water Reuse Symp., Vol. 1*. AWWA Research Foundation, Denver, Colorado.

GWI (2009). Municipal water reuse markets 2010. Global Water Intelligence, Oxford.

Harnett, J., & Hall, P. (1979). Wastewater Reclamation for the San Francisco Bay Regions. *Proc. Water Reuse Symp., Vol. 1*. AWWA Research Foundation, Denver, Colorado.

Health Canada. (2010). *Canadian Guidelines for Domestic Reclaimed Water for Use in Toilet and Urinal Flushing*. Retrieved August 2014, from http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/reclaimed_water-eaux_recyclees/index-eng.php

Heaton, R. (1978). *Planning for Water Reuse in Denver, Colorado*. In "Planning for Water Reuse" D. D. Baumann and D. M. Dworkin, Maaroufa Press, Inc., Chicago, p.161.

Hermanowicz, S., Sanchez-Diaz, E., & Coe, J. (2001). Prospects, problems and pitfalls of urban water reuse: a case study. *Water Science and Technology, 43*(10), 9-16.

Home, F., & Hazel, G. (1979). Regional Water Reuse in Southern California. *Proc. Water Reuse Symp., Vol. 1*. AWWA Research Foundation, Denver, Colorado.

Huang, J. (1979). Toward the Goal of Direct Water Reuse: What Should We Do Next?. *Proc. Water Reuse Symp., Vol. 1*. AWWA Research Foundation, Denver, Colorado.

Isaacson, M. (1979). Epidemiological Studies to Assess the Health Effects of Reclaimed Water Consumption by an Urban Population. *Progr. Water Technol.*, 11, p.209.

Kinkade-Levario, H. (2007). Design for water: Rainwater harvesting, stormwater catchment, and alternate water reuse. New Society Publishers.

Larkin, D. (1979). Reuse Planning at East Bay Municipal Utility District. *Proc. Water Reuse Symp., Vol. 3*. AWWA Research Foundation, Denver, Colorado.

Lee, M., & Reuter, L. (1979). Multipurpose Water Treatment System Development. *Proc. Water Reuse Symp., Vol. 2*. AWWA Research Foundation, Denver, Colorado.

Letcher, R., Jakeman, A., & Norton, J. (2006). Ten iterative steps in development and evaluation of environmental models. *Environmental modeling & software, 21*(5).

Lohman, L. (1979). A Preliminary Analysis or the Political Tensions Affecting Planned Reuse of Water in the Colorado River Basin. *Proc. Water Reuse Symp., Vol. 2*. AWWA Research Foundation, Denver, Colorado.

Madancy, R. (1979). OWRT's Water Reuse Research and Development Program. *Proc. Water Reuse Symp., Vol. 1*. AWWA Research Foundation, Denver, Colorado.

Mattock, G. (1978). *New Processes of Wastewater Treatment and Recovery*. Ellis Horwood Ltd., Chichester, England.

McVicar, M., Anderson, L., Zevenhuizen, E., Mackie, A., Walsh, M., & Gagnon, G. (2012). Water reclamation and reuse. *Water Environment Research, 84*(10).

Miller, R., & Lambert, W. (1979). Human Factors in Design and Operation of Water Reuse Facilities. *Proc. Water Reuse Symp., Vol. 2*. AWWA Research.

Milliken, J., & Trumbly, A. (1979). Municipal Recycling of Wastewater. *Journal American Water Works Association*, 71, p.548.

Milliken, J. (1979). Overcoming Legal and Institutional to Planned Reuse of Water in the Colorado River Basin. *U. S. National Tech. Info. Service* Rep. No. PB-297 270; Select Water Resources Abstracts.

Milliman, J. (1978). *Economic Considerations in the Reuse of Urban Water*. In "Planning for Water Reuse" D. D. Baumann and D. M. Dworkin, Maaroufa Press. Inc. Chicago. p.37.

Molinos-Senante, M., Hernandez-Sancho, F., & Sala-Garrido, R. (2013). Tariffs and cost recovery in water reuse. *Water Resources Management*, 1797-1808.

Nasiri, F., Savage, T., Wang, R., Barawid, N., & Zimmerman, J. (2013). A system dynamics approach for urban water reuse planning: a case study from the Great Lakes region. *Stochastic Environmental Research and Risk Assessment*, 675-691.

Nelson, D., & Cox, P. (1979). Decision Parameters for Combined Use of Effluent Discharges, Surface Flows, and Groundwater. *Water Resources Bulletin*, 15, p.706.

Olson, B., Henning, J., Marshack, R., & Rigby, M. (1979). Educational and Social Factors Affecting Public Acceptance of Reclaimed Water. *Proc. Water Reuse Symp., Vol. 2*. AWWA Research Foundation, Denver, Colorado.

Sims, J., & Baumann, D. (1978). *Psychological Acceptance of Renovated Wastewater: Professional and Public*. In "Planning for Water Reuse" D. D. Baumann and D. M. Dworkin, Maaroufa Press, Inc., Chicago, p.75.

Smith, D., & Laughton, R. (1979). Development of Two Stage and Solid Waste Treatment Systems with Potential for Water Reuse and Energy Recovery. *Proc. Water Reuse Symp., Vol. 2*. AWWA Research Foundation, Denver, Colorado.

Smith, D. (1980). Water reclamation and reuse. *Journal (Water Pollution Control Federation)*, 1242-1284.

Smith, S., & Guild, K. (1984). Development of Tucson metropolitan wastewater reuse program. *Presented at Water Reuse Symposium 3,* San Diego, California.

Thomas, R. (1979). Influence of the Clean Water Act on Wastewater Reuse Planning. *Proc. Water Reuse Symp., Vol. 1*. AWWA Research Foundation, Denver, Colorado.

Torrice, M. (2011). Challenges to water reuse. *Chemical & Engineering News, 89*(17), 38-39.

U.S. Environmental Protection Agency (1992). *Guidelines for Water Reuse*..EPA/625/R-92/004, U.S. Environmental Protection Agency, Center for Environmental Research Information, Cincinnati, Ohio.

UNESCO (2009). World water assessment program. *The United Nations World Water Development Report 3: water in a changing world*. UNESCO, Paris and Earthscan, London.

Vassos, T. (June, 2014). Water Reclamation & Reuse: Understanding the promise - and the potential. *Municipal World*, 27-30.

Wassermann, K., & Radimsky, J. (1979). Water Reclamation Efforts in California. *Proc. Water Reuse Symp., Vol. 1.* AWWA Research Foundation, Denver, Colorado.

WaterSMART Solutions Ltd. (2013). *Water Reuse in Alberta: Experiences and Impacts on Economic Growth.*

Weinberger, L. (1978). *Industrial Water Reuse*. In "Planning for Water Reuse" D. D. Baumann and D. M. Dworkin, Maaroufa Press, Inc., Chicago, p.91.

Williams, R., & Faisst, J. (1979). Treatment Technology for Water Reuse. *Proc. Water Reuse Symp., Vol. 2*. AWWA Research Foundation. Denver. Colorado.

Zimmerman, J., Mihelcic, J., & Smith, J. (2008). Global stressors on water quality and quantity. *Environmental Science & Technology*, 4247–4254.

Chapter 3

Methodology for the Development of the Decision-Making Framework

The following chapter presents a description of the methodology used to guide the development of the stormwater reuse decision-making framework, as well as the decision-making framework itself. The first subsection identifies the research questions and guiding principles used to ensure that the decision-making framework satisfies its intended objectives throughout the phases of its development. Guiding principles, such as robustness and transparency, were selected in order to periodically assess the quality of the decision-making variables and the networks of relationships chosen to construct the reuse framework. The second subsection presents the major decision-making categories chosen to be included in the framework, as well as the subcategories of variables to be considered within each major category. The major decision-making categories are as follows: (1) technical factors; (2) physiographic and climatic factors; (3) legislative and social factors; and (4) economic factors. The third subsection discusses the methods utilized to build the decision-making framework and map the connections it depicts between variables. This subsection briefly discusses the main components of an environmental system model and the process of defining the inputs and outputs of the decision-making framework. The fourth subsection presents the final decision-making framework, as well as a description of each relationship depicted within the framework. Relationships between variables are categorized as being either “driver” or “barrier” relationships, depending on whether a given variable increases or decreases the occurrence of another variable. The final subsection provides a brief summary of the chapter’s findings.

3.1 Overview of Framework Development Strategy

In order to develop a decision-making framework that is scientifically sound and reliable in application, it is necessary to first establish a strategy for its development. The strategic steps adopted by this thesis are outlined in this section.

Prior to framework construction, it is necessary to develop a set of guiding principles to assess the quality the framework throughout the various stages of its development. These principles are intended to ensure that every aspect of the framework is aligned with the overall objectives of framework development, namely the construction of a framework which is accessible to municipalities and provides dependable guidance on stormwater reuse planning and implementation.

The next step involves the selection of the major decision-making categories to include in the framework. Category selection is aided by knowledge accumulated from an extensive literature review, the results of which were presented in Chapter 2. Once the categories are selected, a detailed description of each category is provided. This description includes the definition of sub-categories which may influence the decision-making process, as well as a discussion of how each sub-category impacts reuse planning and implementation. For example, one of the major decision-making categories is ‘technical factors’, and its sub-categories are ‘stormwater characterization’ and ‘stormwater reuse system design’.

Once the main framework variables are selected and discussed, overall framework structure must be assessed. This step includes: (a) deciding upon the configuration of the framework (i.e. the order/placement of each step in the framework), (b) defining framework inputs and outputs, and (c) identifying potential relationships between decision-making sub-categories.

The final decision-making framework is presented in a two-part process. The first part depicts the overall decision-making pathway which a municipality must undertake to determine the inputs (i.e. factors impacting reuse projects) and outputs (i.e. reuse system component design) for a given stormwater reuse project. The second part presents a detailed depiction of the decision-making categories, sub-categories, and relationships between the various sub-categories.

The following sections will detail each of the steps in the above strategy.

3.2 Research Questions and Guiding Principles

The proposed framework is intended to satisfy a number of guiding principles to ensure its success in municipal applications. This subsection presents the guiding principles which have been selected and the rationale for selecting each principle.

The following guiding principles have been selected to assess the overall quality of the reuse framework:

- Easy to use;
- Understandable;
- Transparent;
- Justifiable;
- Robust.

Due to the fact that municipalities will be the primary users of the framework, it is essential that the proposed framework be reasonably easy to use and understand. The framework’s users may be comprised of a variety of professionals from technical and non-technical backgrounds, including environmental scientists, engineers, and urban planners. As a result, the proposed framework must map and explain the complex relationships among stormwater reuse variables using clear, simple terminology without compromising the intellectual integrity of the content. Ultimately, the primary aim of the framework is to distill a wide array of data on the practice of stormwater reuse into a comprehensible and succinct tool to guide municipalities in their reuse implementation efforts.

Additionally, the framework must be scientifically sound and, as a result, should aim to be transparent throughout its development and in the decision-making procedure it presents. Maintaining transparency is a critical element in garnering public trust in the decisions aided by the framework. It also increases the confidence of the municipality in choosing to adopt the framework. Transparency involves the intentional minimization of uncertainty and doubt by maintaining open decision-making channels between decision-maker(s) and stakeholders and the clear communication of the methods used to reach conclusions in the development of the framework (Sa-nguanduan & Nititvattananon, 2011). The framework must also be justifiable in the variables and relationships it presents, as well as decision-making guidance it provides. In addition to providing a logical explanation for the decisions made in constructing the framework, justifiability requires the use and presentation of credible scientific references to support these decisions.

Finally, robustness should be a critical aspect of framework development. Robust decision-making involves the use of systematic strategies to make decisions which minimize susceptibility to uncertain future scenarios (Kim et al., 2015). Robust decisions must be adaptive in nature; they must be made using methods which respond to emerging information, thus developing over time.

The five guiding principles presented above are used to guide the process of framework development presented in the following subsections. Additionally, they will be used to assess the developed framework and discuss its limitations in the next chapter.

3.3 Selection of Major Decision-Making Categories

The purpose of selecting major categories for the decision-making framework is to form an organizational backbone for the framework. In order to meet the guiding principles outlined by the previous subsection, the major categories are critical in ensuring that the framework is clear and easily navigable by the end user(s). The primary end users of the framework are municipalities. However, due to the interdisciplinary nature of stormwater reuse projects, the framework must also be accessible to stakeholders who may be involved in the decision-making process (e.g. developers; urban planners; homeowners).

An extensive literature review was undertaken to aid in the selection of the most representative decision-making categories. The review spanned journal articles and legislation on water reuse from the 1970s onwards, primarily within North America.

The following four major decision-making categories were selected:

- Technical factors (e.g. stormwater characterization; sizing and configuration of reuse components)
- Physiographic and climatic factors (e.g. climate; hydrology)
- Legislative and social factors (e.g. relevant legislation; public perception studies)
- Economic factors (e.g. costs of reuse implementation; cost implications to municipal water treatment facilities)

Each of the above categories plays a role in the planning and implementation of stormwater reuse in urban areas. Sa-nguanduan & Nititvattananon (2011), Barbosa et al. (2012), and Goonrey et al. (2009) all present similar categories for decision making related to stormwater management and/or water reuse projects.

3.3.1 Technical Factors

Stormwater harvesting and reuse is capable of providing for a substantial percentage of an urban area's water demands. However, several technical variables will influence the percentage reduction in potable water demand achieved by stormwater reuse. These variables include the magnitude of water demand, temporal changes in water demand, watershed characteristics, available stormwater detention storage, magnitude of runoff, and temporal changes in runoff within a given watershed. It is important to note that these variables interact in complex ways to influence achievable potable water savings (Mitchell et al., 2007).

Technical factors which must be considered prior to the implementation of stormwater reuse in a mixed-use community are primarily concerned with the proper design and configuration of a stormwater reuse system. In addition to the design aspect itself, the specification of a suitable stormwater reuse system depends upon the proper characterization of stormwater at the location of interest.

3.3.1.1 Stormwater Characterization

Stormwater characterization involves the following factors: (1) defining the quantity and quality of stormwater; (2) monitoring of key stormwater parameters; and (3) modeling of stormwater behaviour (Barbosa et al., 2012). The following subsections identify the considerations which may be involved in undertaking each of these factors.

a) Quantity and Quality of Stormwater

The implementation of stormwater reuse at any scale in an urban environment requires the completion of a rainfall-runoff assessment. It is crucial to determine the quantity of runoff generated at the scale of interest (McArdle et al., 2011). A typical rainfall-runoff assessment involves the acquisition of discharge data for a stream in the vicinity of the reuse project. This will provide a preliminary assessment of the relationship between rainfall and runoff in the area of interest. If the stream or catchment of interest is ungauged (i.e. no discharge data are available), then either of the following approaches may be utilized: (1) development of a desktop rainfall-runoff model to provide a runoff estimate; (2) installation of a gauging station at the location of interest to measure discharge. Robust rainfall-runoff assessments require the use of both approaches; measurements from the gauging station would be used to validate and parameterize the desktop model (McArdle et al., 2011).

In addition to quantity assessment, the quality of stormwater must be evaluated. A sampling program based on storm event occurrence would help determine runoff quality where reuse is to be implemented. Ideally, samples would be collected throughout the storm event, thus yielding a distribution of runoff quality and event mean concentrations across the discharge hydrograph (McArdle et al., 2011). McArdle et al. (2011) achieve their stormwater quality sampling objectives by equipping the gauging station with a data logger. The data logger may be programmed to automatically sample for a specific set of chemicals within set time intervals.

b) Monitoring of Key Stormwater Parameters

Urban stormwater characterization is a challenging task for municipalities and one of the main challenges is the lack of a unique means of data acquisition for runoff quality and quantity monitoring. This is primarily due to the fact that urban runoff is highly site- and region-specific, making it difficult to identify a universal method that would be appropriate for all studies. However, Barbosa et al. (2012) state that a monitoring program for urban stormwater runoff should be guided by the following factors: local characteristics, budgetary and time constraints, and overall study objectives.

A robust stormwater monitoring program should ensure that it achieves the following (Barbosa et al., 2012):

- Identify critical variations in the quality and quantity of stormwater in a given region, typically based on the characterization of seasonal changes;

- Within a given season, characterize the changes throughout a precipitation event by ensuring that sample collection is conducted at several time increments in the event's occurrence;
- Ensure that the monitoring protocol, equipment, and site selection are aligned with the objectives of the monitoring program and representative of the data resolution required to meet said objectives.

c) Modeling of Stormwater Behaviour

The determination of stormwater quality is a critical factor in the reuse decision-making process. Some form of stormwater treatment is required prior to reuse and it is crucial to establish a guiding baseline for treatment objectives. In the event that there is insufficient monitoring data, models may be used to determine runoff quality. Stormwater quality modeling attempts to assess the relationship between site-specific characteristics and potential pollutant concentrations (Barbosa et al., 2012). The primary variables of interest in the development of these models are total rainfall, rainfall intensity, duration of rainfall events, traffic patterns, land use patterns, total drainage area, and antecedent dry periods (Barbosa & Fernandes, 2009).

In addition to aiding in stormwater quality prediction, stormwater quantity may also be established through modeling. The three main types of models for urban runoff quantification are: design storm event method; continuous simulation method; derived probability distribution method (Chen & Adams, 2007).

The design storm event method uses the assumption that a known return period is associated with the design storm, yielding a runoff hydrograph with that same return period. This method has been criticized for the fact that it uses only a limited frame of reference (i.e. the design storm) in the assumption that it characterizes the various meteorological states influencing runoff generation (Chen & Adams, 2007). Ultimately, a 10-year or 100-year design storm cannot anticipate the full range of variability which may be experienced by the drainage system, especially when a design storm is calculated using historic meteorological data which does not account for the potential influence of climate change scenarios.

The continuous simulation method utilizes computer modeling to provide a holistic conceptualization of the hydrologic cycle, including specific storm characteristics and the frequency of storm events. Typically, the output generated provides statistical information on runoff generated by the modeled system configurations. The primary disadvantage of this method is the fact that it is computationally demanding; a significant number of simulations must be conducted to provide a representative assessment of the drainage system in question (Chen & Adams, 2007).

The derived probability distribution method is based on the theory that a dependent random variable's probability distribution can be predicted using functional relationships between the dependent variable and the independent random variables which are related to it (Chen & Adams, 2007). In runoff quantification studies, this theory is applied to the development of rainfall-runoff transformations which aid in the design of probabilistic runoff simulation models depicting physical rainfall and runoff processes in a given region. These transformations vary widely in complexity based on the variables used in their formulation. For example, a simple rainfall-runoff transformation utilizes the runoff coefficient and the volume capacity of depression storage in a given region. Increasingly complex transformations typically utilize more representative hydrologic factors than the runoff coefficient (e.g. infiltration).

Typically, stormwater quantity modeling yields more reliable results than stormwater quality modeling. This is primarily due to the difficulty in anticipating runoff pollutant concentrations following the first flush in a rainfall event (Barbosa et al., 2012). The first flush is a term used to describe the phenomenon whereby the majority of a runoff event's pollution load is conveyed in the initial fraction of the total event volume (Taebi & Droste, 2004). The first flush is difficult to predict due to the large disparity between its pollution load from one event to the next even within the same watershed (Barbosa et al., 2012).

3.3.1.2 Design Aspects of Stormwater Reuse Systems

The design of stormwater reuse systems requires the determination of four critical variables. In their design of a stormwater reuse system to meet potable end uses in

Newcastle, Australia, McArdle et al. (2011) note the importance of specifying the following four variables:

- Retention: location and storage capacity of the retention basin which is used to collect raw runoff from the municipal stormwater system (e.g. stormwater management/retention pond);
- Treatment: maximum capacity required to ensure proper treatment prior to reuse;
- Pump: capacity required to transfer collected stormwater from retention basin to treatment units, as well as capacity for other transfers such as reclaimed stormwater distribution;
- Pipe size: length and diameter necessary to transfer water from one system component to the next (e.g. from stormwater retention pond to treatment units).

Two general design philosophies exist for the implementation of reuse projects: centralized and decentralized approaches (McArdle et al., 2011). Centralized reuse involves the collection of stormwater from a wider catchment area, conveyance to a central treatment plant, and distribution to a potentially large customer base. This approach enables the implementation of reuse on a larger scale than decentralized reuse. However, centralization involves several challenges including: (1) the difficulty in controlling harvested stormwater quality due to the wider collection area; (2) financial hurdles due to the significant infrastructure demands; and (3) potential issues in planning and implementation due to the involvement of multiple jurisdictions. Decentralized reuse is implemented at the household or community scale (e.g. residential sub-division; single commercial site). In this case, the aspects of the reuse system (collection, treatment, and distribution) are contained within the household or community, and typically monitored by the end users. As a result, decentralization does place responsibility upon the user(s) to maintain runoff quality and ensure proper system functionality. However, troubleshooting problem areas in the reuse system is often easier due to the constrained area within which reuse is applied. It is important to note that decentralized reuse is typically implemented by designers in new urban developments; implementation in existing urban developments is limited (McArdle et al., 2011).

The following subsection provides a discussion of design considerations for the collection, treatment, storage, and distribution of stormwater for centralized and decentralized reuse.

a) Stormwater Collection

Stormwater runoff is intermittent in nature and, as a result, detention and storage are critical components in a reuse project (McArdle et al., 2011).

The first process in the stormwater reuse train is collection. Typically, capturing a large percentage of the total annual rainfall-runoff will depend upon the collection of small to medium events.

The collection of stormwater may be achieved by using either one of the following methods (Mitchell et al., 2007):

1) Traditional drainage system (gutter, pipe, and channel components);
2) Conduit system utilizing low-impact development techniques (e.g. swales; bio-retention cells).

The use of a traditional drainage network for stormwater collection requires the consideration of water losses through exfiltration, which may occur through cracks in network piping and/or the present of unlined network channels. In addition, it is important to note the conveyance capacity of a given drainage system. Typically, drainage systems are sized to transport design flows with 2-year to 10-year return periods. As a result, traditional drainage systems are generally sized appropriately for the collection of stormwater deemed harvestable (Mitchell et al., 2007).

In low-impact development conveyance networks, stormwater travels through vegetated channels or cells. These networks may include one or more of the following components: vegetated swales; bio-retention filters; filter drains. These typically experience water losses initially during a rainfall-runoff event due to the limited infiltration capacity of each component, as well as losses through soil infiltration. As a result, it is necessary to estimate these two types of losses in low-impact techniques prior to implementation in a stormwater harvesting project. Initial losses during a runoff event are dependent upon local climate conditions and the evapotranspiration potential of the low-impact network, while exfiltration losses are dependent upon soil type (Mitchell et al., 2007). Mitchell et al. (2007) investigated both types of losses and concluded that (a) medium to high imperviousness must be present in the community where stormwater is harvested otherwise collection losses may be too high, and (b) low-impact systems in high porosity soils (e.g. sandy soils) must be lined to prevent excessive collection losses due to exfiltration.

It is important to note that the use of low-impact development techniques for the collection of stormwater is an application which requires further research and refining. This is primarily due to the fact that traditional usage of low-impact techniques have focused upon achieving pollution control and flood protection objectives rather than stormwater harvesting (Mitchell et al., 2007). However, Mitchell et al. (2007) note the potential of integrating low-impact techniques with stormwater collection to achieve multiple benefits. These benefits include providing a potable water supply alternative, improving aesthetics of urban settings, and decreasing pollutant loading to surface waters during storm events.

b) Stormwater Treatment Prior to Reuse

The selection of an appropriate treatment method requires knowledge of the following parameters: quality and quantity of stormwater for the area of interest; volume control requirements; treatment requirements; local traits impacting system construction.

A variety of pollutants may be carried by urban stormwater runoff from sources such as vehicle emissions, paved surfaces, and wastes from anthropogenic sources. These pollutants include hydrocarbons, nutrients, pesticides, and metals (Jang et al., 2010). Table 1, adapted from Hvitved-Jacobsen et al. (2010), presents the six main groups of pollutants found in urban stormwater. Stormwater treatment methods used in runoff management typically capture and detain runoff for a time period defined by the rate of settling or filtering of pollutants. Examples of such methods include retention ponds, sand filters, vegetated swales, and infiltration trenches (McArdle et al., 2011).

The determination of treatment requirements is dependent upon the end use(s) which the reuse system is intended to meet. Thus far, non-potable end uses which have been investigated for stormwater include the following: garden irrigation; toilet flushing;

firefighting; recharge of groundwater reservoirs; use in industrial applications; bridging environmental flow requirements. The primary challenge in the determination of treatment requirements is the lack of legislation or cohesive guidelines relating to stormwater reuse (Mitchell et al., 2007). Municipalities have often resorted to utilizing wastewater reuse guidelines in the absence of stormwater reuse guidelines due to the more established nature of wastewater reuse in legislation. However, Mitchell et al. (2007) highlight the inadequacy of this practice; the contaminant concentrations, supply, and source of wastewater are characteristically different from those of stormwater.

Table 1 Main pollutant groups found in urban stormwater and their characteristics (adapted from Hvitved-Jacobsen et al., 2010).

Pollutant Group	Monitoring Parameter	Pollutant Source
Suspended solids	Total Suspended Solids (TSS)	Anthropogenic-source waste; construction debris; structural wear of pavements; etc.
Biodegradable organic matter	BOD_5; COD	Animal waste; vegetation; etc.
Organic micropollutants	PAHs; PCBs; Endocrine disruptors; etc.	Tire and pavement abrasion; combustion of fossil fuels; construction debris; etc.
Pathogenic microorganisms	E.coli; Total coliforms	Animal-source contributions
Heavy metals	Lead; Nickel; Copper; Zinc; Cadmium; Chromium	Tire abrasion; fuel/oil leaks; industrial emissions; etc.
Nutrients	Phosphorous; Nitrogen	Fertilizers; settling of atmospheric particulates

Mitchell et al. (2007) investigated and discussed three main categories of stormwater treatment techniques: (1) physico-chemical treatment; (2) bio-filter treatment; (3) extended treatment trains utilizing low-impact development techniques.

Physico-chemical stormwater treatment employs techniques which are common to drinking water and wastewater treatment. An example of a physico-chemical stormwater treatment train is the one designed for the Santa Monica Urban Runoff Recycling Facility. The first step in this treatment facility is screening of coarse and fine particles. Next, a dissolved air flotation device is used to remove oil and grease. Finally, microfiltration is coupled with ultraviolet disinfection to yield the treated stormwater (Boyle Engineering Corporation, 1999).

Bio-filtration treatment techniques utilize a filter composed of a particular soil medium which is strategically planted to remove specific pollutants from runoff. A collection pipe would be installed to transport the treated stormwater to a storage compartment downstream (Hatt et al., 2005). The specific mechanisms for the removal of pollutants within the bio-filter involve a combination of physical, chemical, and biological removal mechanisms. An example of a physical, chemical, and biological removal process would be mechanical filtration, adsorption to soil particles, and nutrient uptake by microbes respectively (Mitchell et al., 2007). The main advantage of using bio-filters for stormwater treatment applications is that they allow the specification of filtration media which target specific pollutants depending on the characteristic composition of runoff in a given area.

Extending the use of low-impact techniques for the treatment of runoff is an option which requires further research. The use of retention ponds, vegetated swales, and/or constructed wetlands to treat runoff has been investigated at a small scale in the literature. However, it is still unclear whether or not these techniques may be relied upon to achieve a consistently treated effluent given a varied range of rainfall-runoff events. In addition, the performance of low-impact techniques will depend greatly upon the hydraulic loading they receive and, as such, this factor warrants further research (Mitchell et al., 2007).

Finally, it may be necessary to implement a bypass mechanism prior to the treatment components to respond to high storm flows. The bypass would minimize sediment re-suspension and scouring of formerly settled components (Mitchell et al., 2007).

c) Stormwater Storage Prior to Reuse

Storage requirements for stormwater reuse applications are a critical aspect of implementation in urban areas due to space limitations. The primary objective of stormwater storage is to maximize the reliability of the storage volume while minimizing the necessary size, and thus cost, of the storage compartment (Mitchell et al., 2007).

Mitchell et al. (2007) provide guidance for end-use-based stormwater storage based on two distinct rainfall/runoff characteristics:

1) Regions with constant rainfall/runoff patterns: Selection of end uses with primarily constant water demand patterns is more favourable than end uses with seasonal demand patterns (e.g. green space irrigation); smaller storage would be required to reliably meet the needs of end uses with constant demand patterns;
2) Regions with primarily seasonal rainfall/runoff patterns: The selection of end uses is not as dependent upon the type of end use demand; both indoor and outdoor water demands may be met due to their predominantly constant pattern of demand on an annual basis.

In the majority of cases, stormwater storage needs are deemed non-limiting given the presence of a back-up water supply to be used in the event of a shortage in reuse water (e.g. back-up potable supply pipe) (Mitchell et al., 2007).

d) Stormwater Distribution for Reuse

In urban areas, the reuse of stormwater for non-potable end uses typically involves the implementation of a third-pipe network to meet distribution needs. Generally, the density of urban areas makes the necessary pipe construction an expensive option for municipalities. However, focusing reuse implementation efforts on planned mixed-use communities would make pipe construction costs more manageable. This is due to the fact that pipe construction in established urban areas may cost roughly 2.5 times greater than in new developments (McArdle et al., 2011).

For stormwater reuse, the type of distribution system necessary relies upon a number of factors, including:

- Spatial scale of region which the distribution system serves;

- Density and distribution of the end use demands.

Overall, two different types of stormwater distribution systems may be implemented: (1) open space irrigation systems; (2) non-potable (dual) distribution systems (Mitchell et al., 2007).

It is important to note that the research pertaining to the distribution of recycled wastewater is exchangeable with the distribution of recycled stormwater. Although other aspects of wastewater versus stormwater reuse may not be comparable (e.g. treatment requirements), distribution system design requirements for stormwater reuse may draw upon those in wastewater reuse.

3.3.2 Physiographic and Climatic Factors

The quality and quantity of stormwater in a given urban area will be influenced by the physiographic and climatic factors within that area. Barbosa et al. (2012) list the following physiographic/climatic characteristics as being influential to stormwater management: climate; land; soils; hydrology; topography. It is important to note that "land" does not only refer to land use, but also the availability of space (i.e. high versus low density) for stormwater reuse applications (Barbosa et al., 2012). Also, the variable "soils" refers to soil type as well as coverage/continuity in a given urban area.

The main variables influencing the quantity of runoff are the climate and hydrology in a given area (Barbosa et al., 2012). Specifically, estimating runoff loads for an event requires data on the drainage area, as well as rainfall amount and intensity (Brezonik & Stadelmann, 2002).

3.3.3 Legislative and Social Factors

Roy et al. (2008) state that the main reason for the resistance to change in stormwater management is the complexity of risk factors involved. A lack of certainty in the nature and probability of risks involved leads to the hesitancy by specialists and the general public to adopt management measures, including but not limited to the reuse of stormwater. Gaining social acceptance for stormwater reuse applications is a factor which has garnered significant attention from the scientific community. Roy et al. (2008)

emphasize that the two fundamental factors in increasing social acceptance of reuse initiatives are public education and the implementation of pilot studies to demonstrate reuse system performance.

Prior to undertaking the task of stakeholder engagement, municipalities must first identify the stakeholders which may be involved in the planning and implementation of a stormwater reuse project. Sa-nguanduan & Nititvattananon (2011) state that one of the first tasks a municipality should undertake is the identification of all stakeholders who may be impacted by reuse implementation and/or interested in the decisions made regarding reuse. The authors identify three major steps for mapping the stakeholders involved in a given water reuse project: (1) identify stakeholders who are directly or indirectly involved in water management and stormwater management choices (e.g. municipal drainage or stormwater management department; homeowners); (2) conduct interviews with the stakeholders identified in the previous step in order to assess how they may be impacted by reuse planning and implementation; and (3) present stakeholders with the opportunity to relay their perceptions of the roles they play or would play in water reuse projects, and ask stakeholders about the factors involved in why they support, oppose, or are indifferent to the water reuse project in question (Sa-nguanduan & Nititvattananon, 2011). The final step helps municipalities identify the potential fears, motivating factors, and general interests held by the stakeholders involved, which would allow municipalities the opportunity to tailor their public engagement efforts to the specific stakeholder population involved. It is important to note that the task of stakeholder identification is itself a challenging one due to potential overlap in municipal water management responsibilities and the potential involvement of institutional or public-interest groups with competing priorities. The authors identify three categories of stakeholders which may be identified for urban water reuse projects: primary stakeholders (persons/groups directly affected by the reuse initiative, primarily the producers and consumers of the reuse water); secondary stakeholders (typically municipal/provincial departments which act as a mediator between the municipality and the primary stakeholder groups, helping to manage various aspects of reuse planning and implementation, e.g. Ministry of Natural Resources); and tertiary stakeholders (persons/groups who are not directly affected by the reuse project, but may play a role in influencing public perception of the project, e.g. non-governmental organizations) (Sa-nguanduan & Nititvattananon, 2011).

Kaplowitz and Lupi (2012) stress the importance of incorporating stakeholder input into stormwater management projects. Ensuring that stakeholder feedback is integrated into project decisions is critical to public support throughout the planning and implementation stages. The authors detail the design and implementation of a choice experiment survey in order to gain knowledge about public support, or lack thereof, for various stormwater Best Management Practice (BMP) alternatives. The authors targeted residential landowners due to the fact that available information on residential BMP preferences in the literature is sparse. In general, environmental decision-making processes are found to be more strongly supported if they engage all stakeholders in meaningful ways (Webler & Tuler, 2006). Surveys have frequently been used by planners and scientists to gauge public values and preferences for specific watershed management efforts. There has been a steady increase in the complexity of survey techniques (Kaplowitz & Lupi, 2012). In addition to the meaningful engagement of stakeholders, it is crucial to ensure that stakeholder involvement is not restricted or biased towards particular members of the public; input should be elicited from the general local population in watershed planning (Junker et al., 2007).

In addition, engaging stakeholders in stormwater management projects ensures increased support for public policies and fosters more informed public policy choices. The U.S. Clean Water Act (Phase II) states that watershed planning processes require public participation and education (Environmental Protection Agency, 2000).

McArdle et al. (2011) note that the storage requirements for stormwater runoff in a reuse project may generate public opposition. Ensuring the allotment of adequate storage space within urban communities is a critical part of the reuse planning process. The authors present three potential hurdles to public acceptance of stormwater recycling projects:

1) Public health concerns: documentation and implementation of stormwater recycling projects is sparse and sometimes unavailable to the general public, thus increasing the degree of scepticism by the public (Dolnicar & Schafer, 2009);

2) Economic concerns: members of the public may anticipate a rise in water costs, and may be concerned about whether or not project costs will be transferred – either directly or indirectly – to consumers;
3) Environmental/social concerns: the implementation of stormwater reuse requires the use of land for the installation of necessary infrastructure (e.g. retention pond; treatment units). The general public may be concerned about the use of land with either existing or potential social and environmental value to the community.

Wu et al. (2012) discuss the importance of addressing public health concerns due to their being a documented challenge in water reuse implementation. The authors noted that public perception of health risk tied to treated stormwater use was highly dependent upon the end use proximity to users.

Barbosa et al. (2012) emphasize the necessity of properly managing the social aspects associated with stormwater management in general. Stormwater management efforts, which may include stormwater reuse, must utilize methods which consider public area management, spatial planning, education, recreation, and maintenance, as well as more subtle influencing factors like culture. Successful management initiatives require the cooperation of municipal drainage departments and planning departments, in addition to consultation with the public and other municipal departments (Barbosa et al., 2012).

In Canada and the United States, there are significant inconsistencies in the management of stormwater and its reuse. There is no national legislation concerning stormwater reuse to guide jurisdictions. In many cases, stormwater reuse projects draw upon research and legislation related to wastewater reuse which is often inadequate in addressing certain challenges unique to stormwater reuse (e.g. collection of runoff; treatment of urban-source runoff).

Water reuse literature frequently cites public health concerns, and sometimes environmental concerns, for the reluctance of municipalities in adopting reuse projects. Water reuse legislation has the potential to mitigate public health and environmental risks associated with water reuse practices and play an important role in managing public perception of reuse, especially in addressing recycled water quality concerns (Paranychianakis et al., 2015). Currently, there is no globally recognized legislation guiding water reuse implementation. The aforementioned lack of consistency in legislative reuse guidance is a hurdle which can be observed amongst different countries, states/provinces, and even individual municipalities. Historically, water reuse legislation has been dictated by two significant reuse documents: (1) the World Health Organization water reuse recommendations (World Health Organization, 1989); and (2) the regulations specified by the State of California (State of California, 2000). The World Health Organization criteria, although addressing a limited scope of reuse applications and considering only cost-efficient treatment technologies, presented an important milestone in reuse legislation. The California regulations are more relevant to current water reuse projects, outlining treatment options and limits leading to the production of safe reuse water.

3.3.4 Economic Factors

The costs associated with the implementation of stormwater reuse systems must be integrated into the entire project life, starting at the earliest decision-making stages. The various costs associated with reuse implementation are listed below (Barbosa et al., 2012):

- Construction costs;
- Operational costs;
- Maintenance costs;
- Monitoring and follow-up costs;
- Other costs, including but not limited to component life and replacement costs; staff training costs; public consultation and survey costs; compliance assurance and enforcement.

One of the challenges in the adoption of stormwater reuse is the scarcity of reliable cost and performance data, which would be beneficial in the evaluation of costs associated with different reuse options. Although cost evaluation may be conducted without cost data from previous applications, the process would benefit from the examination of costs in existing stormwater reuse projects. The lack of widely available and complete data on costs continues to be a hurdle in the widespread adoption of reuse projects.

The implementation of stormwater reuse in an urban community involves the simultaneous management of cost, performance, and long-term risk. Brown and Humphrey (2005) detail a decision-making method called Infrastructure Asset Management (IAM) which achieves these management objectives. IAM is a multi-disciplinary management approach used to anticipate and manage the long-term performance of urban infrastructure/systems (e.g. water reuse systems) using specific software tools to minimize public risk and maximize infrastructure service life.

3.4 Considerations in Framework Construction, Mapping of Variable Interactions, and Final Framework Presentation

This subsection presents the critical factors considered throughout the development of the decision-making framework and provides the rationale for crucial framework structure and content decisions. The relationships between the decision-making variables presented in Subsection 3.3 are also highlighted in this subsection. It is paramount that the nature of correlations and interactions between the variables are well-justified and meet the guiding principles outlined in Subsection 3.2. The final decision-making framework is presented at the end of this subsection.

3.4.1 Factors Influencing Framework Construction

Two primary types of environmental system models exist: (1) research models, and (2) management models (Lin, 2003). The decision-making framework presented by this thesis is fundamentally a management model. Thus, it is primarily concerned with aiding municipalities in their water resources management efforts as it pertains to the implementation and management of stormwater reuse systems.

In order to design a coherent decision-making framework for the management of an environmental system (e.g. stormwater), it is crucial to identify the discrete system components which must be involved in the construction of the framework: A “system” is defined as an object where various types of variables interact, resulting in the generation of observable outputs; “outputs” are signals which can be observed; “inputs” are signals which are measurable and can be monitored by an observer; "state variables" define the condition of the system but may not be observable; and "parameters" define the interactions between state variables (Lin, 2003). Figure 1, adapted from Lin (2003), depicts the components in environmental system models.

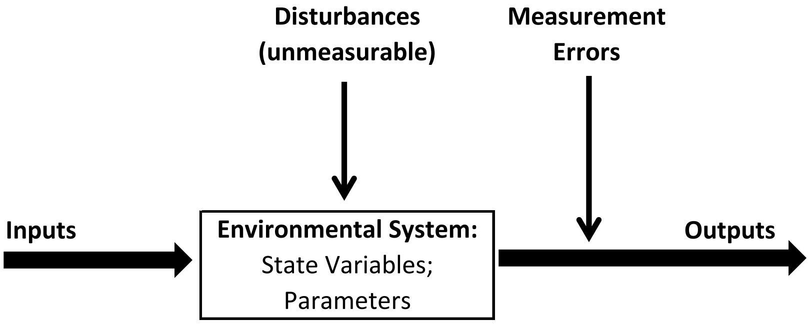

Figure 1 Environmental system model components (adapted from Lin, 2003).

Although the decision-making framework for stormwater reuse will not be a complete, technical model of reuse implementation, it will attempt to achieve a precursory step to model development known as System Identification (SI). SI is a procedure whereby the nature of relationships between system inputs, state variables, and system outputs is established (Lin, 2003). The decision-making framework presented herein will rely upon an extensive literature review to establish the relationships between the variables involved in stormwater reuse implementation. However, it must be noted that the framework is intended to provide a starting point for municipalities considering the implementation of stormwater reuse; the majority of the variables presented by the framework will be case-specific and cannot be fully anticipated by the framework. As a result, the decision-making framework presented herein is fundamentally a screening-level or baseline framework intended to present a starting point for municipalities considering the adoption of stormwater reuse. It is then the responsibility of a municipality to tailor the framework to the specific objectives surrounding their adoption of stormwater reuse.

In the development of the framework, an important aspect was the avoidance of an issue known as problem displacement. Problem displacement is cited as a potential issue in environmental planning and management efforts whereby a recommended solution does not solve the actual problem but rather presents a fragmented solution which focuses on a single/limited aspect of the problem (Korhonen, 2007). As a result, using a systems approach to environmental planning and management problems is critical to avoiding issues associated with problem displacement. A systems-based method not only assesses each component present in the system, but also the relationships and interactions amongst the different components. The stormwater reuse decision-making framework is constructed with a systems-design approach in mind. However, due to the fact that the framework attempts to present a holistic view of the variables involved in reuse implementation, its development was an iterative process owing to the complexity of natural and societal system interactions. An iterative framework development procedure involves the periodic assessment and revision of all framework aspects (e.g. structure; decision-making variables; variable interactions) as further information is gathered. Also, it is necessary to acknowledge the dynamic nature of the reuse framework; future application of the framework may necessitate further revisions to its content and structure.

It is important to note that the design of a stormwater reuse system which is properly integrated into the local and regional scale of the urban water cycle requires an iterative design methodology which not only incorporates the four major decision-making criteria, but also ensures that the role of the criteria within the overall water management context is investigated.

When a municipality is considering the implementation of a stormwater reuse system, it is crucial that they not only consider the aforementioned variables, but also decide upon the overall objectives and constraints of reuse implementation within their municipality (Zhen et al., 2006). Reuse project objectives are typically tied to cost, water quantity, and/or water quality. Frequently, these economic and technical aspects of reuse implementation are the only decision-making factors taken into consideration (Sa-nguanduan & Nititvattananon, 2011). The stormwater reuse framework presented at the end of this chapter attempts to combat this tendency in municipal decision-making by providing a holistic view of reuse implementation (i.e. involving social, law, and physiographic/environmental factors). However, it is also important that a municipality define their local reuse objectives and stakeholder interests as a preliminary step in the planning phase; these will ultimately play a significant role in determining the decision-making factors to consider and selecting the preferred reuse system alternative for implementation (Sa-nguanduan & Nititvattananon, 2011).

3.4.2 Construction and Presentation of the Final Framework

The first step in framework construction involves defining the input and output variables among the decision-making factors presented in the Subsection 3.3. The technical factors were divided into stormwater characterization, which was assigned to the inputs group, and design aspects of reuse systems, which was assigned to the outputs group. All other factors (physiographic/climatic; legislative and social; economic) were assigned to the inputs group. The rationale for these input/output divisions is as follows: the input factors are ones which must be researched early in the reuse planning phase; knowledge of these input factors is ultimately required to make a decision in the reuse system implementation phase and dictate outputs, such as the stormwater collection method(s) and stormwater storage tank size/location. Figure 2 depicts the inputs and outputs chosen to construct the final framework. It is important to note that there must be a feedback loop between the inputs and outputs as shown in the final framework structure. The dynamic nature of the decision-making factors, as well as their complex interactions, make it necessary to review the researched inputs upon deciding on the reuse system outputs to confirm that all variables and their impacts have been taken into account. Iteration is a crucial part of ensuring the robustness of the decisions made using the framework.

Finally, it is crucial that both the short- and long-term planning aspects are taken into account for each factor and potential driver/barrier relationship. For each factor involved, it is not only necessary to evaluate its current state (e.g. current stormwater runoff quantity available for collection), but also one or more future state (e.g. anticipated stormwater quantity available in 10 years, 20 years, etc.).

Decision-making Framework

INPUTS	**Technical Factors - Stormwater Characterization** Quantity/quality of stormwater; monitoring of key parameters; modeling stormwater behaviour
	Physiographic and Climatic Factors Climate; land; soils; hydrology; topography
	Legislative and Social Factors Assessment of risk factors; stakeholder engagement; applicable legislation
	Economic Factors Construction costs; operational costs; maintenance costs; monitoring costs; other costs

OUTPUTS	**Technical Factors - Design Aspects of Reuse Systems** Stormwater collection; treatment; storage; distribution

Figure 2 Input and output factors comprising the stormwater reuse decision-making framework.

The developed framework is comprised of two individual parts which are presented in Figures 3 and 4. Figure 3 presents the overall decision-making structure for the implementation of stormwater reuse. Figure 4 presents a detailed depiction of the decision-making factors that affect reuse implementation, as well as the nature of the relationships between the individual variables involved in the decision-making process. Relationships between variables are categorized as drivers, barriers, or potentially both depending on the circumstances surrounding reuse adoption.

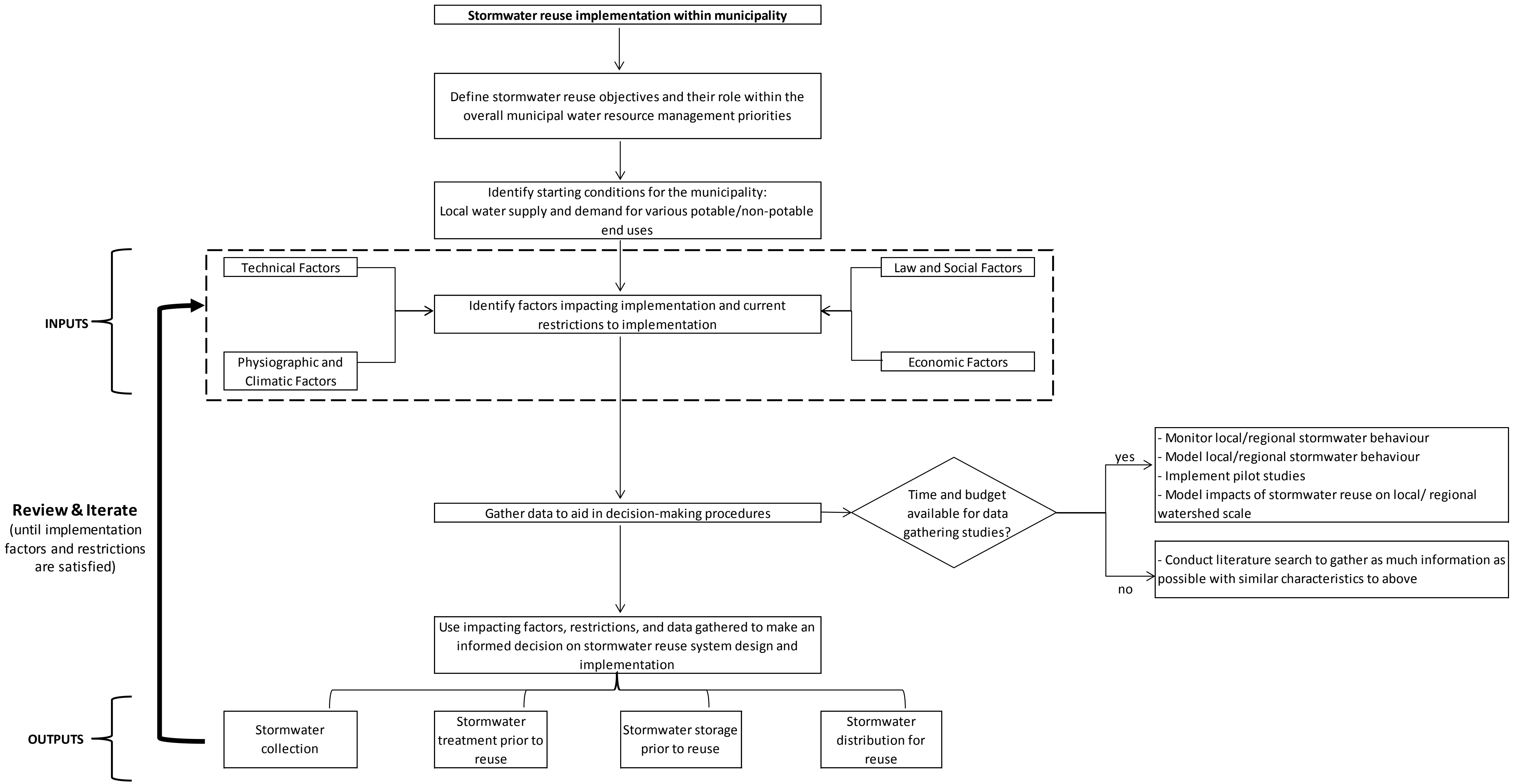

Figure 3 The final decision-making framework for stormwater reuse implementation in municipalities.

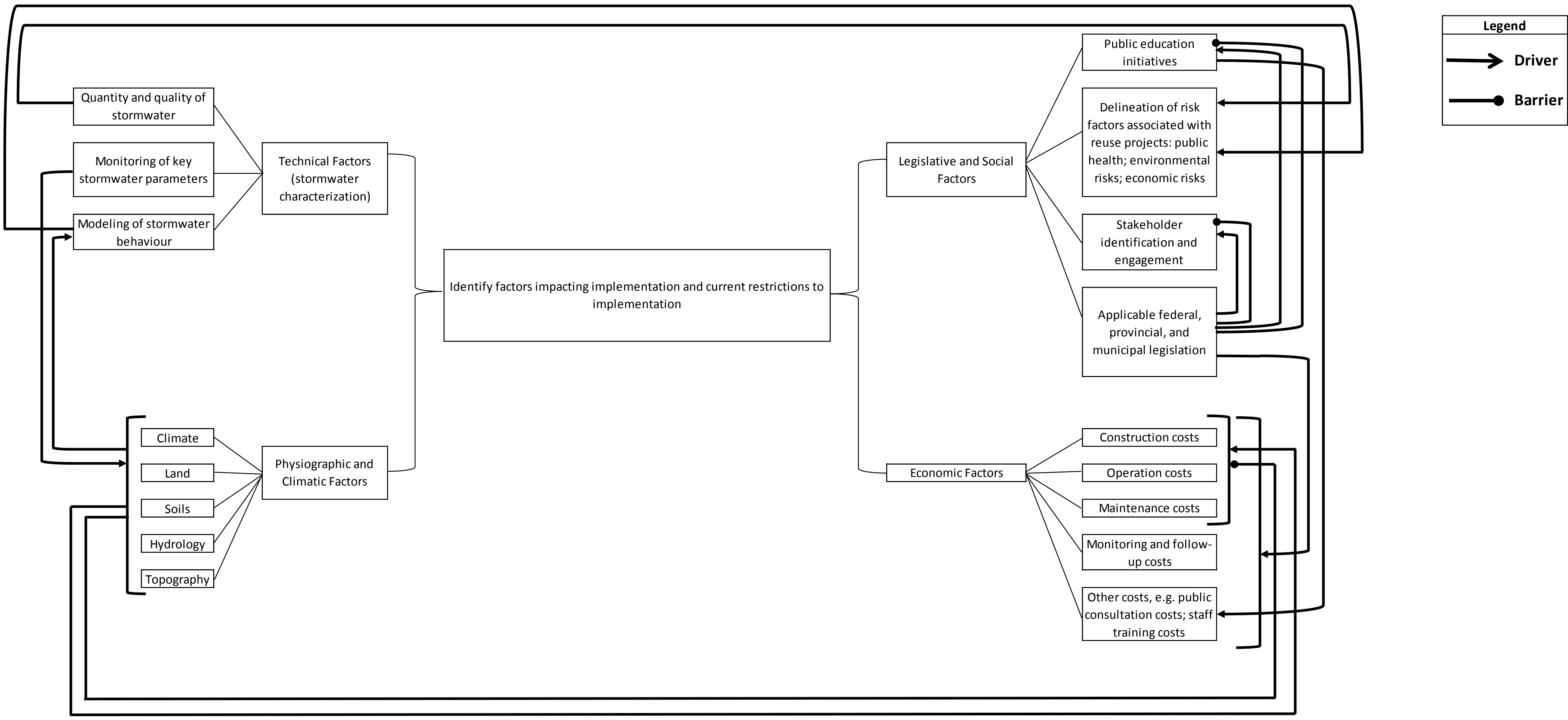

Figure 4 Detailed decision-making factors impacting stormwater reuse implementation.

The following is a description of the driver/barrier relationships depicted in the decision-making factors flowchart (Figure 4):

- Legislation (law and social factor) may act as either a driver or barrier to different aspects of reuse implementation projects. For example, public policy which focuses on water resource conservation may aid in reuse adoption, while policy which encourages water resource development may discourage reuse (Asano, 2007). In addition, stakeholder engagement and public education initiatives (law and social factors) may be aided or deterred by existing legislation (law and social factor), depending on whether or not legislative guidance is available for municipalities on these aspects.
- Determining the quantity and quality of stormwater (technical factors) acts as a driver to the delineation of health, environmental, and economic risk factors (law and social factors) potentially associated with reuse. Defining the quantity of stormwater runoff generated provides decision-makers with a figure of anticipated reuse water supply which may be used to augment the drinking water supply and contribute to water conservation efforts (Asano, 2007). In turn, this information will help assess potential economic risks (e.g. costs savings from decreased potable water demand; financial capital required to establish collection/storage facilities required to process the collected stormwater). Defining the quality of stormwater runoff gives decision-makers a starting point for determining health risks which may be associated with reuse, environmental risks which may result from stormwater collection system malfunctions, and economic risks tied to stormwater treatment costs based on its initial quality (Paranychianakis et al., 2015).
- The monitoring of key stormwater parameters (technical factor) may be a driver for knowledge of climate, land, soils, hydrology, and/or topography (physiographic/climatic factors) for the reuse project implementation site. A stormwater monitoring program typically involves components such as stream monitoring and baseflow studies (hydrology), as well as infiltration/runoff monitoring (soils) (Barbosa et al., 2012).

- The modeling of stormwater behaviour (technical factor) is a driver towards the delineation of risk factors associated with reuse projects (law and social factor). Stormwater modeling can play an important role in predicting behaviour and assessing the potential financial payback from reuse adoption (by predicting runoff generation and, therefore, stormwater volumes which can be collected for reuse) and the ability of stormwater reuse to meet current water demands and limit water resource stresses/shortages (i.e. environmental risks) in the future (McArdle et al., 2011).
- The determination of physiographic and climatic factors (e.g. land use; hydrology) aids in the modeling of stormwater behaviour (technical factor). For example, researching the land use designations of the project site and surrounding properties will aid in assessing the percent imperviousness in the stormwater model which, in turn, will help determine the relative magnitude of stormwater runoff versus infiltration (Barbosa et al., 2012).
- Site-specific physiographic and climatic factors may act as either a driver or barrier to construction, operational, and maintenance costs (economic factors) (Barbosa et al., 2012). For example, topography and soil conditions in a given site may either increase or decrease cost estimates for reuse system construction and component installation efforts; climate may ease or exacerbate reuse system construction, operation, and maintenance requirements depending on temperature maxima and minima, precipitations amounts, and severity of winter months.
- Public education initiatives (law and social factor) act as a driver to ‘other’ costs (economic factor). Public meetings, information sessions, and educational newsletters require specific budgetary considerations in reuse project planning and implementation (Kaplowitz & Lupi, 2012).
- Applicable federal, provincial, and municipal legislation (law and social factor) may be either a driver or barrier to stakeholder identification and engagement (law and social factor). Barbosa et al. (2012) stress the influence of policy on public participation and public perception of stormwater management initiatives, which may include reuse. If reuse legislation encourages or enforces stakeholder participation, then it will drive municipalities to identify and engage relevant

stakeholders. However, legislation that does not address stakeholder participation, or a lack of legislation relevant to reuse, may present a barrier to stakeholder engagement. Legislation has the potential to provide critical guidance to municipalities considering the adoption of stormwater reuse; stakeholder identification and engagement is one aspect of reuse which may benefit from this guidance (Sa-nguanduan & Nititvattananon, 2011).

- Applicable federal, provincial, and municipal legislation (law and social factor) may be either a driver or barrier to public education initiatives (law and social factor). As stated above, legislation may play an important role in guiding the municipal implementation of reuse projects, including public education efforts associated with these projects.
- Applicable federal, provincial, and municipal legislation (law and social factor) can be a driver for construction, operation, maintenance, monitoring, and other costs (economic factors), depending on the particular provisions within the legislation. For example, legislation which prescribes the treatment requirements of stormwater collected for reuse may play a role in increasing construction, operation, and maintenance costs depending on the type of treatment components needed to meet physical, chemical, and biological treatment levels.

An example of framework application to a case study will be presented in Chapter 4 in order to better illustrate the practical utilization of the reuse framework.

3.5 Summary

This chapter provided a description of the critical factors considered in constructing the stormwater reuse decision-making framework, from structural framework considerations to content-specific considerations. The final two-part framework was presented along with a description of the variable relationships depicted by the framework. Framework validation and an analysis of framework limitations will be presented in the following chapter.

3.6 References

Asano, T. (2007). Water reuse: Issues, technologies, and applications. McGraw-Hill.

Barbosa, A., & Fernandes, J. (2009). Assessment of treatment systems for highway runoff pollution control. Water Science & Technology, 1733-1742.

Barbosa, A., Fernandes, J., & David, L. (2012). Key issues for sustainable urban stormwater management. Water Research, 6787-6798.

Boyle Engineering Corporation. (1999). Engineering Report for Dry-Weather Runoff, Reclamation, Storage, Pumping, Distribution, and Nonpotable Water Use Area Facilities. City of Santa Monica.

Brezonik, P., & Stadelmann, T. (2002). Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota. Water Research, 1743-1757.

Brown, R., & Humphrey, B. (2005). Asset management for transmission and distribution. IEEE Power and Energy Magazine, 39-45.

Chen, J., & Adams, B. (2007). Development of analytical models for estimation of urban stormwater runoff. Journal of Hydrology, 458-469.

Dolnicar, S., & Schafer, A. (2009). Desalinated versus recycled water: Public perceptions and profiles of the accepters. Journal of Environmental Management, 888-900.

Environmental Protection Agency (EPA). (2000). Storm water phase II final rule: An overview. EPA 833-F-00-001.

Goonrey, C., Perera, B., Lechte, P., Maheepala, S., & Mitchell, V. (2009). A technical decision-making framework: stormwater as an alternative supply source. Urban Water Journal, 417-429.

Hatt, B., Siriwardene, N., Deletic, A., & Fletcher, T. (2005). Novel bioretention systems for stormwater treatment and reuse - Laboratory scale performance testing. 10th International Conference on Urban Drainage. Copenhagen, Denmark.

Hvitved-Jacobsen, T., Vollertsen, J., & Nielsen, A. (2010). Urban and highway stormwater pollution. Taylor and Francis Inc.

Jang, Y., Jain, P., Tolaymat, T., Dubey, B., Singh, S., & Townsend, T. (2010). Characterization of roadway stormwater system residuals for reuse and disposal options. Science of the Total Environment, 1878-1887.

Junker, B., Buchecker, M., & Muller-Boker, U. (2007). Objectives of public participation: Which actors should be involved in the decision making for river restorations? Water Resources Research, 43(10).

Kaplowitz, M., & Lupi, F. (2012). Stakeholder preferences for best management practices for non-point source pollution and stormwater control. Landscape and Urban Planning, 364-372.

Kim, Y., Chung, E., & Jun, S. (2015). Iterative framework for robust reclaimed wastewater allocation in a changing environment using multi-criteria decision making. Water Resources Management, 295-311.

Korhonen, J. (2007). Environmental planning vs. systems analysis: Four prescriptive principles vs. four descriptive indicators. Journal of Environmental Management, 51-59.

Lin, Z. (2003). Modeling environmental systems under uncertainty: Towards a synthesis of data-based and theory-based models. Athens, Georgia: University of Georgia.

McArdle, P., Gleeson, J., Hammond, T., Heslop, E., Holden, R., & Kuczera, G. (2011). Centralised urban stormwater harvesting for potable reuse. Water Science & Technology, 16-24.

Mitchell, V., Deletic, A., Fletcher, T., Hatt, B., & McCarthy, D. (2007). Achieving multiple benefits from stormwater harvesting. Water Science & Technology, 135-144.

Paranychianakis, N., Salgot, M., Snyder, S., & Angelakis, A. (2015). Water reuse in EU states: Necessity for uniform criteria to mitigate human and environmental risks. Critical Reviews in Environmental Science and Technology, 1409-1468.

Roy, A., Wenger, S., Fletcher, T., Walsh, C., Ladson, A., Shuster, W., et al. (2008). Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. Environmental Management, 344-359.

Sa-nguanduan, N., & Nititvattananon, V. (2011). Strategic decision making for urban water reuse application: A case from Thailand. Desalination, 141-149.

State of California. (2000). Code of regulations, Title 22, Div. 4, Chapter 3: Water recycling criteria. Berkeley, California.

Taebi, A., & Droste, R. (2004). First flush pollution load of urban stormwater runoff. Journal of Environmental Engineering and Science, 301-309.

Webler, T., & Tuler, S. (2006). Four perspectives on public participation process in environmental assessment and decision making: Combined results from 10 case studies. Policy Studies Journal, 699-722.

World Health Organization (WHO). (1989). Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture . Geneva, Switzerland: WHO Technical Report Series 778.

Wu, Z., McKay, J., & Keremane, G. (2012). Issues affecting community attitudes and intended behaviours in stormwater reuse: A case study of Salisbury, South Australia. Water, 835-847.

Zhen, J., Shoemaker, L., Riverson, J., Alvi, K., & Cheng, M. (2006). BMP analysis system for watershed-based stormwater management. Journal of Environmental Science and Health Part A, 1391-1403.

Chapter 4

Decision-Making Framework Application and Discussion of Limitations

The following chapter presents a discussion of two potential methods for the assessment of framework performance. In addition, it provides an example of framework application to a case study in southeastern Ontario, as well as an analysis of framework limitations. Recommendations for future work and framework development are also discussed.

4.1 Assessing Decision-Making Framework Performance

The following subsection presents a discussion of two potential methods for the assessment of framework performance: (1) the use of Sustainable Development Indicators for the assessment of water reuse projects; and (2) the use of the guiding principles presented in Subsection 3.2 of Chapter 3.

4.1.1 Assessment Method 1: Sustainable Development Indicators

One method to assess reuse framework performance is the use of Sustainable Development Indicators (SDIs) to periodically evaluate its performance throughout its application to a stormwater reuse project.

SDIs are defined as factors which can be used to assess the progression of a given project towards sustainable development goals and, where necessary, correct the project's path if it is deemed misaligned with sustainable development objectives (Palme, 2010). The definition of sustainable development varies from one field to another and is often debated within different fields. Depending on the field in question, the specific targets used to achieve sustainable development may vary. However, the most commonly cited definition of sustainable development was presented in the Brundtland Report and states the following:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (United Nations World Commission on Environment and Development, 1987)

In addition to being developed on international, national, and community scales, SDIs have been developed for a variety of sectors (e.g. business sector; public service sector). SDIs related to water supply and treatment have been developed and examples of these indicators include water reuse, water availability/extraction, and the fraction of the population with access to drinking water. Water-specific SDIs are often developed for water utilities to assess the sustainability of urban drinking water and wastewater treatment systems. A set of SDIs for a municipal water utility may evaluate the following variables: emissions associated with operating the water system (e.g. carbon dioxide); system robustness (i.e. ability to adapt to changes in supply and demand, and potential future uncertainty); opportunity for research and development; system costs; benefits to the community; public engagement; health and safety (Palme, 2010). These SDIs may play an important role in urban water resource planning and management.

Sustainable Development Indicators pertaining to water reuse may be applied in the assessment of the performance of the stormwater reuse decision-making framework. Indicators for water reuse applications may be categorized broadly using the following factors: environmental; economic; technical; social; and institutional (Upadhyaya & Moore, 2012). Social factors include metrics such as public acceptance and health impacts, while technical factors include the quantity and quality of reclaimed water available. The indicator system presented by Upadhyaya and Moore (2012) provides just one example of a SDI-based assessment method for water reuse projects.

It is important to note that SDI metrics should not be viewed as a fixed system; rather, the periodic review and assessment of the relevance and representativeness of these metrics is an important part of the SDI process (Palme, 2010). Additionally, the development of more SDI metrics is a crucial part of the learning process which must be undertaken by municipalities. It is necessary to ensure that the indicators used to assess reuse implementation are viewed as a continuously-evolving method for evaluation and framework validation.

The application of Sustainable Development Indicators will not only serve to evaluate the performance of the decision-making framework, but will also provide a means for municipalities to learn about stormwater reuse and document the experience of its implementation. Ultimately, the goal of this performance validation exercise is to compile a tangible body of knowledge on municipalities' experiences with stormwater reuse implementation. It is anticipated that the increased documentation of various reuse projects will facilitate the development of a set of best practices for reuse implementation.

It is important to note that the completion of SDI assessments may be regarded by municipalities as a time-consuming administrative burden (Palme, 2010). However, the benefits associated with these assessments are twofold; not only do they provide a concrete means of tracking the experience of stormwater reuse implementation and benchmarking performance, they also provide municipalities with a means of measuring and reporting on the value and quality of these new projects for public transparency.

4.1.2 Assessment Method 2: Guiding Principles for Framework Development

The principles presented in Subsection 3.2 to guide framework development may be used to assess framework performance during its application to stormwater reuse projects. The five guiding principles – ease of use, understandability, transparency, justifiability, and robustness – are used to develop the assessment criteria presented in Table 2.

Although the assessment criteria presented in Table 2 have been formulated as yes/no questions, the answers to these questions will likely fall on a spectrum between 'yes' and 'no' due to the multifaceted nature of stormwater reuse planning and implementation. As a result, it is recommended that (1) each criterion be rated on a scale (e.g. 1 to 5 with 1 indicating the framework's inability to address a given criterion and 5 indicating its success in meeting the criterion), and (2) each assigned rating be given a written justification specifying how the framework does or does not meet particular aspects of a given criterion.

Table 2 Criteria for the assessment of framework performance using the guiding principles presented in Subsection 3.2.

Guiding Principle	Assessment Criterion
Ease of Use	Are municipalities capable of adopting the framework autonomously without needing to enlist the help of external technical/academic sources?
	Can decision-makers follow the steps outlined in the framework without encountering any gaps in the process?
Understandability	Is the language used in the framework clear to decision-makers from a variety of technical and non-technical backgrounds?
	Is framework configuration and sequence of steps logical to decision-makers from a variety of technical and non-technical backgrounds?
Transparency	Does the use of the framework encourage the identification of stakeholders involved in stormwater reuse projects?
	Does the use of the framework encourage open communication between decision-makers and stakeholders?
	Does the use of the framework in the implementation of stormwater reuse contribute to increased public trust and minimize uncertainty associated with municipal decision-making?
Justifiability	Does the framework lead to logical decisions regarding the various aspects of stormwater reuse implementation?
	Can the decisions made using the framework be traced back and justified by a credible reference in the scientific literature?
Robustness	Can the decision-making framework allot for and adapt to uncertain future scenarios?
	Can the decision-making framework anticipate factors influencing reuse projects in scenarios which vary temporally and spatially?

4.2 Case Study: Framework Application to Proposed Mixed-Use Community

The following subsection presents a discussion of a case study involving a proposed mixed-use community development. The developer would like to assess the feasibility of implementing stormwater reuse in the community, which is located in southern Ontario. The specific location of the subject site will remain confidential as per the developer's specifications. The case study data were obtained through an internship with s2e Technologies Inc. from September to December 2013.

4.2.1 Site Description and Project Background

The subject site (Subject Site X), located in southern Ontario, is currently a 30-hectare greenfield which is surrounded primarily by medium- to high-density residential developments. The developer is planning to locate a mixed-use community at this site. The site plan details the following land use designations within the community: medium- to high-density residential; commercial/retail/office; public open space/park; public roads. The concept plan for Subject Site X is presented in Figure 5.

Figure 5 Concept plan for the proposed mixed-use community to be located at Subject Site X (AECOM Canada Ltd., 2012).

Table 3 depicts the proposed division of land use within Subject Site X. The percentages in parentheses indicate the percent of total site area occupied by a given land use.

Table 3 Land use breakdown by area within the proposed Subject Site X.

Type of Land Use	Land Area (hectares)	Percent of Total Site Area
Medium-density residential	3.30	11%
Medium-high density residential	13.41	45%
Mixed use (commercial/retail/office/residential)	8.08	27%
Public open space/park	1.36	5%
Public roads	3.91	13%
Total	30.06	

The primary challenge associated with the development of Subject Site X is its proximity to a stream (Stream Y) which is known to contain cold-water fish populations. Stream Y has been identified as an environmentally sensitive coldwater stream. As a result, the developer is required by the local Conservation Authority to minimize the impact of urban runoff to the stream and maintain aquatic health. A Municipal Environmental Study Report prepared for the proposed development states that there may be long-term impacts associated with the urban runoff from the site, as well as the construction of stormwater management facilities (e.g. stormwater retention ponds).

The proposed stormwater management system for Subject Site X initially involved the following components: (1) an infiltration basin (1.90 hectares); (2) a two-tier retention pond comprised of a sediment forebay and wet pond for peak flow and quantity control (2.55 hectares); and (3) an infiltration channel (1.25 hectares). These three components are connected in series by either storm sewer network segments or overland flow sections (AECOM Canada Ltd., 2012). Only the infiltration channel was proposed to be located within Subject Site X (along the western site boundary); all other components were to be located offsite on adjacent properties. The stormwater system is intended to manage flows within Subject Site X as well as the residential properties adjacent to the site. As a result, the three components of the stormwater management system are significant in size and stormwater retention capacity. Thus, the Environmental Study Report anticipates potential adverse environmental impacts from the construction and/or possible malfunction (e.g. clogging of infiltration components) of the stormwater management system.

4.2.2 Example of Decision-Making Framework Application

4.2.2.1 Defining Stormwater Reuse Objectives

The first step in the decision-making framework involves the identification of reuse objectives within the overall municipal water resource management priorities. In this case, the developer of Subject Site X is interested in assessing the feasibility of stormwater reuse implementation in the mixed-use community in order to (a) minimize potential adverse impacts associated with urban runoff to Stream Y, and (b) contribute to stormwater management onsite without relying completely on retention and infiltration, thus minimizing the space and capacity requirements for the proposed stormwater management system. It is crucial for the developer to maintain aquatic health within Stream Y as this is a requirement by the local Conservation Authority. Construction activities and post-development stormwater contributions by Subject Site X may adversely impact stream healthy by increasing stream discharge, altering baseflow contributions, increasing water temperatures, and reducing water quality (e.g. increased turbidity).

In 2014, the municipality within which Subject Site X is located implemented storm drainage charges in order to finance storm sewer network repairs and the projected expansion of urban land uses requiring new drainage networks. In terms of overall municipal water resource management, the implementation of stormwater reuse would decrease the stress imposed upon already burdened and aging stormwater drainage infrastructure. In addition, stormwater reuse would aid in municipal water conservation efforts by decreasing the subject site’s reliance on drinking water to meet all its water demands.

It is important to note that this first step in the decision-making framework requires consultation with the municipality, drinking water treatment plant, and local

Conservation Authority in order to assess each party's priorities and concerns relating to stormwater reuse adoption.

4.2.2.2 Water Supply and Demand for the Mixed-Use Community

The next step in the decision-making framework is the identification of initial conditions for Subject Site X through the determination of water supply and demand requirements for potable and non-potable end uses. The purpose of this procedure is to assess site-specific water needs for various end uses before beginning the planning phase for a stormwater reuse system. It is crucial to understand the potential non-potable end use demands which reclaimed stormwater may be used to meet, as well as the projected demand volumes which the system must be capable of supplying. In addition to site-specific water demands, this step requires the assessment of the cost associated with supplying municipal potable water to the site (based on the projected water demand). The determination of specific supply and demand requirements provides the developer with a baseline for comparing the potential costs and benefits of stormwater reuse adoption. For example, knowledge of the community's water demands by end use makes it possible for the developer to estimate the cost of supplying potable water to meet various end uses, thus providing an initial figure for potential cost savings through the use of reclaimed stormwater instead of potable water.

Table 4 presents the result of average water usage for a single-family residential unit in the municipality within which Subject Site X is located.

Table 4 Average water use by end-use for a single-family residential unit in the Subject Site X municipality (AECOM Canada Ltd., 2012).

Type of End-Use	**Average Water Use for Single-Family Residential Unit**	
	Litres/building/day (lbd)	Litres/capita/day (lcd)
Bath	8.34	3.24
Clothes Washer	101.11	38.89
Dishwasher	22.47	8.64
Faucets	168.52	64.82
Showers	101.11	38.89
Toilets	87.07	33.49
Leaks	42.13	16.20
Total Water Use	530.84	204.17

Since residential land uses accounts for 56% of the total site area, the numbers presented in Table 4 provides a starting point for the estimation of total potable water demand by the community. No estimates could be found for commercial land uses within the municipality of interest. It is recommended that the developer use anticipated occupancy to estimate water usage for the mixed-use buildings on Subject Site X.

4.2.2.3 Identification of Factors Impacting Reuse Implementation

Once a baseline for community water demand is established, the next task is to identify factors impacting implementation and potential restrictions to implementation. Table 5 outlines tasks which the developer may undertake to investigate each of the four decision-making factors. The remainder of this subsection presents an example application of at least one task per decision-making factor in an effort to illustrate a preliminary means of applying the decision-making framework for Subject Site X.

Table 5 Description of potential tasks which may be undertaken to assess factors impacting stormwater reuse implementation.

Decision-Making Factor	Tasks to Investigate Stormwater Reuse Feasibility
Technical Factors	Assess local weather patterns, including historic rainfall volumes/rates and storm severity and frequency
	Provide preliminary assessment of stormwater runoff quality by determining land use onsite and on adjacent properties
	Assess stormwater runoff quantity by estimating the ratio of pervious to impervious area within and adjacent to the mixed-use community
	Conduct a literature review to investigate any past environmental studies or monitoring programs conducted in the vicinity of the subject site
Physiographic and Climatic Factors	Research regional climate data
	Investigate current and historic land uses for the subject site and surrounding properties
	Conduct a search of geotechnical reports published for the site and/or surrounding properties in order to determine soil types, infiltration capacities, topographical data, etc.
	Review any documentation published by the local Conservation Authority and Environment Canada on the watershed/subwatershed within which the site is located to obtain hydrological data (e.g. streamflow)
Legislative and Social Factors	Identify primary, secondary, and tertiary stakeholders which may be involved in stormwater reuse planning and implementation within the community
	Design a stakeholder engagement and education program
	Research relevant federal, provincial, and municipal legislation which may impact stormwater reuse planning and implementation (e.g. the Ontario Building Code; Health Canada's Guidelines for Domestic Reclaimed Water Use in Toilet and Urinal Flushing)
Economic Factors	Calculate capital cost requirements for the implementation of stormwater reuse in the mixed-use community at a combination of scales (e.g. within dedicated land parcels versus within the entire community) and for various non-potable end uses (e.g. toilet flushing; garden irrigation)
	Estimate operation and maintenance costs associated with the potential reuse implementation scenarios
	Assess cost savings incurred by the stormwater reuse system and estimate the payback period for the system

a) Technical Factors

Precipitation is a critical aspect of stormwater reuse planning and implementation. Figure 6 presents a plot depicting the probability of precipitation on a given day in the municipality within which Subject Site X is located. The probabilities presented in the plot are based upon local airport weather station records from the year 1982 to 2012.

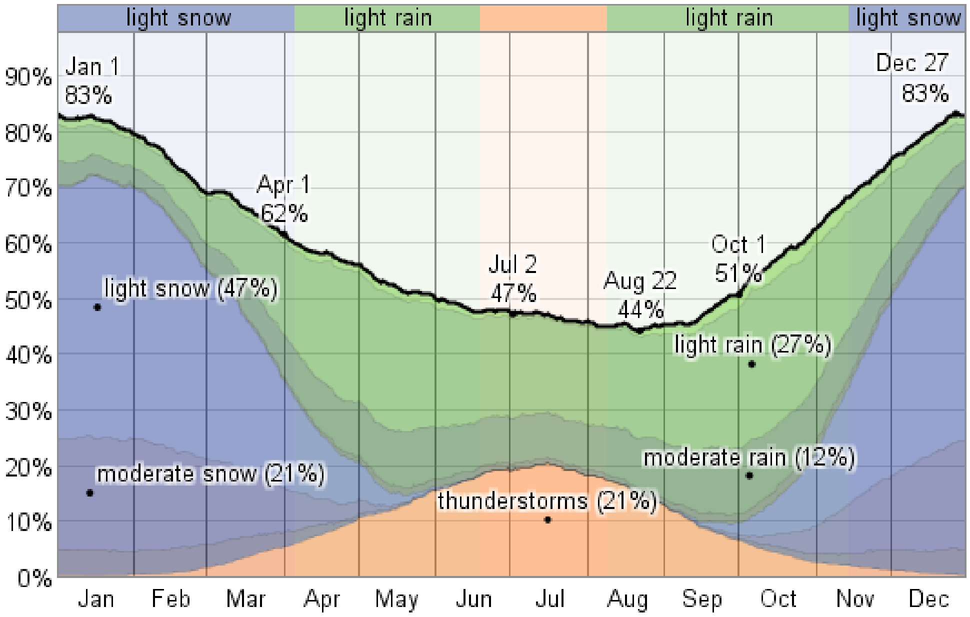

Figure 6 Probability of precipitation on a given day in a year in the municipality within which Subject Site X is located (WeatherSpark, 2012).

The estimation of runoff quantity will not be conducted for this preliminary case study; only runoff quality will be addressed. In order to obtain a preliminary assessment of the runoff quality onsite, it is necessary to determine land use onsite and on adjacent properties. Due to the fact that Subject Site X is currently a greenfield and has not yet been developed, assessing runoff quality may be done by investigating the following:

- Atmospheric pollutants which may be present in the vicinity of Subject Site X, such as the presence of industry or major highways, potentially contributing to stormwater quality degradation;
- Catchment surfaces which the stormwater contacts prior to reaching the collection system which influence the amount of dirt and debris carried by the stormwater. The catchment in this case is comprised of the surfaces over which runoff travels prior to its reaching the collection system.

b) Physiographic and Climatic Factors

A geotechnical investigation was conducted for Subject Site X. Three major soil types have been identified as comprising the geology within the site: (a) moraine-type lake deposits composed of silty sands and silty clays in the southern and eastern portions of the site; (b) silty sand and fine sand deposits in the central portion of the site; and (c) gravelly sand and coarse gravel deposits in the northern and western portions of the site. The most pervious and well-drained portions of Subject Site X are located within the northern and western sections of the site. The least pervious portions of the site are those containing the moraine-type soil deposits in the southern and eastern sections of the site. The geotechnical report also revealed that Subject Site X drains primarily in a northwesterly direction (AECOM Canada Ltd., 2012).

c) Legislative and Social Factors

Stakeholder identification and engagement will be briefly discussed in this subsection.

There are several legislative triggers for Subject Site X which require the mandatory engagement of specific stakeholders. The provincial Conservation Authorities Act requires that the developer engage the local conservation authority since the proposed development falls within the valley and floodplains of the watershed (AECOM Canada Ltd., 2012). In addition, the Ontario Ministry of Natural Resources (MNR) must be consulted in the planning and development of Subject Site X. The MNR may decide to set timing restrictions for construction activities potentially impacting aquatic species within Stream Y. In addition, due to the classification of Stream Y as a coldwater creek, the MNR may choose to place other restrictions to ensure that the development of Subject Site X does not adversely impact baseflow conditions (i.e. groundwater contributions to Stream Y) and the thermal regime of Stream Y. In addition, the local drinking water treatment plant, municipality, and potential homeowners/occupants of the proposed community at Subject Site X must all be engaged and consulted by the developer early in the planning stage of reuse implementation.

The implementation of a stormwater reuse system in Subject Site X may be influenced by certain federal, provincial, and/or municipal policy requirements. Federally, the practice of stormwater reuse is unregulated in Canada. On all regulatory levels, the lack of succinct policy is a significant limiting factor in widespread adoption of stormwater reuse. However, some non-binding guidelines are available for lot-level reuse systems. These guidelines may be adopted for larger-scale implementation. In 2014, the municipality within which Subject Site X is located implemented a stormwater bylaw. This bylaw includes a monthly charge for storm drainage based on land use and size. This specific municipal legislation may be a motivating factor for stormwater reuse due to the fact that collecting stormwater for reuse will contribute to lower runoff rates. The Ontario Building Code (OBC) is the primary regulatory device governing rainwater reuse applications; it allows water of non-potable quality to be used indoors, but it only allows the water to be used for toilet or urinal flushing end uses. The specific provisions within the OBC must be consulted prior to reuse implementation.

d) Economic Factors

An important economic aspect of stormwater reuse implementation within Subject Site X is the consideration of potential runoff contributions from adjacent sites. Specifically, the properties located immediately south and west of Subject Site X contain medium- to high-density residential developments with minimal vegetative cover (AECOM Canada Ltd., 2012). As a result, it is anticipated that these properties would experience lower rates of infiltration during a storm event, thus leading to increased runoff volumes which must be considered in the planning and implementation of stormwater reuse within the subject site.

Calculating the economic benefit of implementing stormwater reuse first requires the determination of the costs associated with a baseline scenario whereby no stormwater reuse is implemented (Scenario A). It is critical to determine two key quantities in baseline Scenario A: (1) the quantity of potable water required to meet the anticipated water demand within the community, and (2) the quantity of runoff generated given that the community is developed as per the proposed site plan (Figure 5) without reuse implementation. Next, it is necessary to quantify the changes associated with reuse implementation (Scenario B). Scenario B requires the developer to estimate the quantity of water to be supplied by the stormwater reuse system, thus enabling the developer to estimate (1) the quantity of potable water saved, and (2) runoff reduction through the collection of stormwater for reuse. These two scenarios will provide the developer with an initial estimate of the cost savings incurred as a result of water savings. In addition, they yield a preliminary assessment of the developer's efforts to minimize adverse impacts to Stream Y through runoff reduction.

Following the identification of factors impacting reuse implementation, the next step involves gathering all the data obtained from the research of factors and determining the data gaps and further research requirements. Further research can be in the form of more extensive literature review or stormwater monitoring and modeling studies depending on time and budget availability.

4.2.2.4 Discussion of Potential Reuse System Designs

Finally, the data gathered throughout the aforementioned steps must be used to make a decision on stormwater reuse system design. Stormwater collection, treatment, storage, and distribution component design must be based upon the data gathered in the previous framework steps. Each component should be designed to meet the site-specific criteria revealed by the technical, physiographic/climatic, legislative, social, and economic factor inputs. For example, stormwater treatment system requirements will be based upon (a) runoff quality (technical factor), (b) runoff quality as dictated by land use (physiographic/climatic factor), and (c) legislative requirements for reclaimed water treatment levels. The design of the stormwater storage component(s) will be based upon (a) system capacity requirements based on anticipated occupancy/demand (dictated by multiple factors, including the determination of the most economic reuse configuration), and (b) space availability within the community for storage component placement (social and physiographic factor, dictated by land use and public consultation).

The data presented by Subsections 4.2.2.1, 4.2.2.2, and 4.2.2.3 can be used to provide a preliminary set of alternatives for the implementation of stormwater reuse within Subject Site X. Due to the fact that the case study presented by this thesis is only preliminary in nature, the alternatives presented herein do not include specific quantitative design criteria. The alternatives will focus on specifying potential reuse system component locations and possible non-potable end uses to be met by the system.

A conceptual depiction of a single stormwater reuse system is presented in Figure 7. Stormwater is first collected in a Stormwater Management (SWM) wet pond. It then flows through an outflow control structure and into a treatment sequence. Although the scope of this report does not provide comprehensive design requirements for stormwater treatment, a typical treatment sequence may include micro-filtration, ultraviolet exposure, and chlorination (Ministry of the Environment, 2003). Finally, the reclaimed stormwater is pumped to a storage tank where it is detained and piped to the end-use locations on demand.

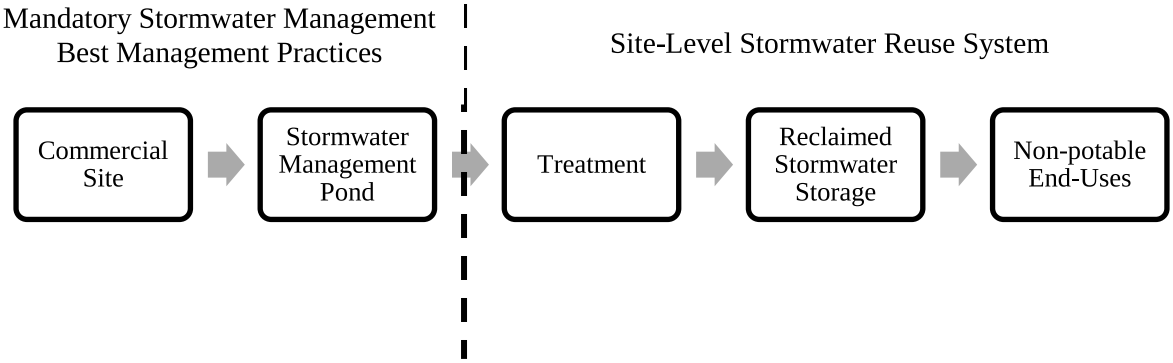

Figure 7 Conceptual diagram of a stormwater reuse system for a commercial site (adapted from Nanos, 2013).

A key concept in the system's design is its emphasis on de-centralization of stormwater collection and storage. Rather than relying on a single storage tank to supply reclaimed stormwater to the entire community, a de-centralized approach focuses on implementing multiple reuse systems throughout the community to meet specific end-uses for different sections. The benefit of this approach is that it minimizes piping requirements since system locations are now in close proximity to the reuse end-location. De-centralization also allows the designer to tailor each reuse system to the part of the community which it serves. This enables the explicit consideration of land use and lifestyle patterns for each plot of land served by its dedicated reuse system. The two critical considerations in de-centralization are the locations of the stormwater storage tanks and the final destination(s) to which the reclaimed stormwater will be pumped. In terms of storage tank locations, the primary goal is to be opportunistic in the selection of spaces within the proposed Subject Site X community layout presented in Figure 5. For example, the site plan depicts a large number of parking lots and spaces. As a result, one consideration for the location of storage tanks would be in unused parking lot or garage corners. Another potential location for stormwater storage would be the construction of a retention pond within one of the parkettes or green spaces onsite.

In terms of the reclaimed stormwater destinations, it is important to note that each reuse option and destination is associated with costs and benefits which depend upon (a) site-specific conditions and (b) overall project objectives. Two potential stormwater reuse implementation alternatives are presented in Figure 8 and Figure 9. Configuration A (Figure 8) focuses on reuse collection, storage, and end uses within the residential building cluster in the northern portion of Subject Site X. Configuration B (Figure 9) focuses on reuse collection, storage, and end uses within the commercial and office building cluster in the southwestern portion of Subject Site X. Depending on budget availability, both configurations may be implemented simultaneously within Subject Site X. Both configurations focus on a specific area within the community in an effort to minimize pumping and piping costs.

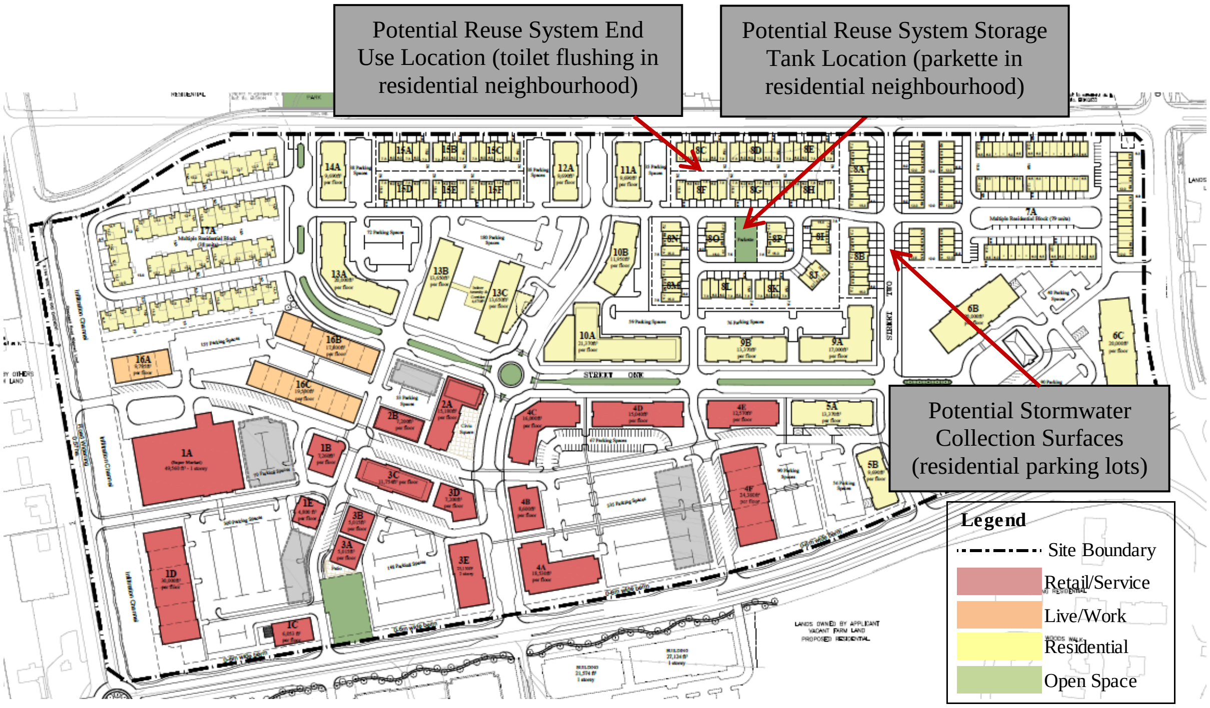

Figure 8 Potential reuse system configuration A. This configuration focuses on reuse within the residential cluster in the northern portion of Subject Site X.

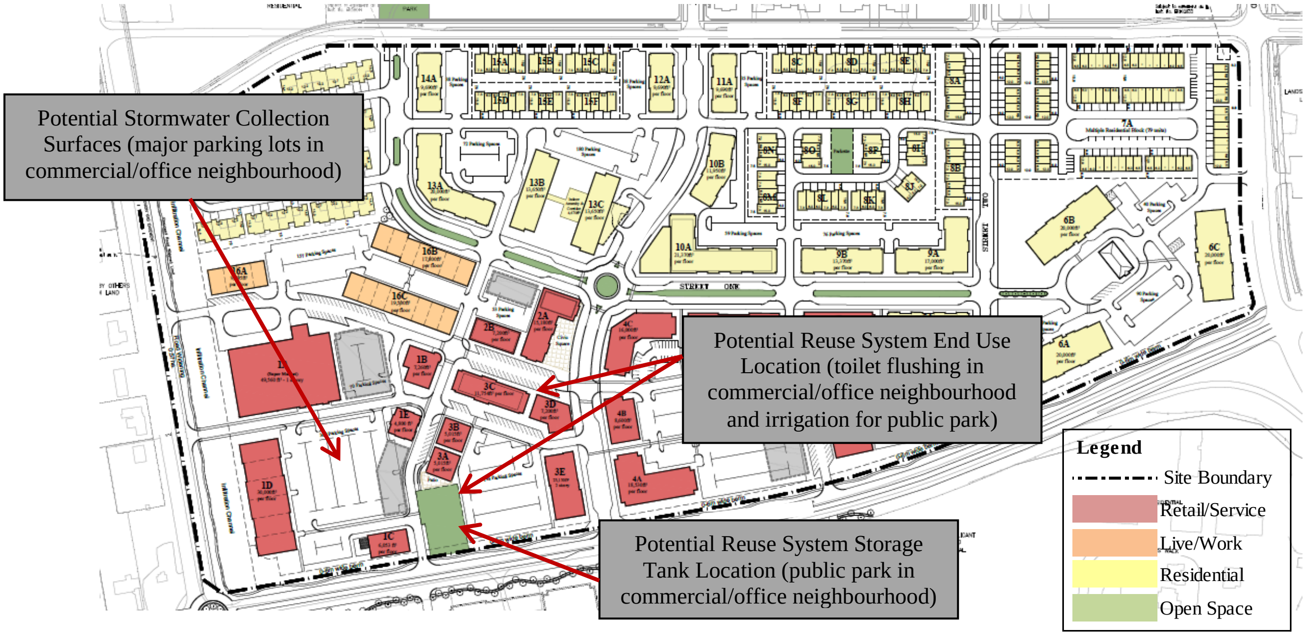

Figure 9 Potential reuse system configuration B. This configuration focuses on reuse within the commercial and office building cluster in the southwestern portion of Subject Site X.

In terms of stormwater storage, various tank types and configurations may be selected. Commercially available tanks types include underground concrete, underground fibreglass, or above ground plastic. Modular tank configurations are also possible. These allow for the use of multiple tank units which may be connected or disconnected depending on space and storage requirements. Storage requirements, space availability, and structural/geotechnical considerations are the primary factors impacting the selection of storage tank material and method of installation (i.e. above ground or underground).

One of the goals in designing the stormwater reuse system is to develop a system which is flexible and adaptable to the community's needs. It is recommended that the storage tank contain backup potable water supply and overflow pipes which help to compensate for discrepancies in stormwater supply and demand. As a result, the design accounts for the anticipated overflow volumes in the storage tank. The back-up supply of potable water is used in dry periods to “top-up” the stormwater tank and ensure that the end-use demands are still being met.

Another design feature of the system is the inclusion of a backflow preventer at the point where the stormwater storage tank connects to the back-up supply pipe. This ensures that the stored stormwater does not contaminate the municipality’s potable water supply by preventing the back-siphoning of stormwater into the back-up system. Using independent plumbing lines is another system feature which works to prevent mains supply contamination. Periodic inspection and testing of the backflow preventer is necessary.

Stormwater reuse system design is the output that must be dictated by the decision-making factor inputs. It is anticipated that the decision-maker will encounter data gaps in the first iteration of the framework. As a result, it is necessary that the decision-making path from inputs to outputs be iterative, with data gaps in the outputs leading the decision-maker towards a more focused review of input factors impacting implementation.

It is recommended that stormwater reuse be implemented along with other measures intended to minimize adverse impacts to Stream Y. For example, the developer should specify a buffer zone surrounding Stream Y within which development would not be allowed. Typically, a 30- to 50-metre buffer zone is implemented around streams to protect them from adverse impacts associated with urban development. Additionally, the developer should consider the implementation of erosion control methods (e.g. silt fences) throughout the construction phase to limit sediment loadings into Stream Y.

4.3 Discussion of Framework Limitations

The following subsection presents a discussion of potential limitations of the decision-making framework in municipal applications, as well as general limitations associated with stormwater reuse implementation.

Chocat et al. (2007) state that the application of decentralized stormwater management options widely and rapidly may result in certain risks. The following three risk factors were outlined: (1) the unknown effects regarding cumulative as well as long term effects; (2) potential tendency of practitioners to implement decentralized solutions as a means of delaying necessary water infrastructure repairs; (3) challenges posed by the integrated operation of centralized and decentralized water systems in the same urban region.

In addition, Zhen et al. (2006) note that stormwater reuse offers one piece of the overall urban stormwater management puzzle. Runoff minimization and water quality improvements in urban areas are the two main priorities of stormwater management, with the provision of reuse options being a secondary goal for many municipalities. As a result, it is necessary to assess the role of stormwater reuse within the overall municipal stormwater management priorities for each reuse project. The first step in the decision-making framework encourages the decision-maker to assess the project's role within municipal water management objectives. The success of stormwater reuse projects requires careful consideration of municipal water management needs on a case-by-case basis.

A critical limitation of the decision-making framework is the fact that it does not explicitly address the role of climate change in stormwater reuse planning and implementation. However, the framework does not exclude the possibility of incorporating the influence of climate change on stormwater reuse projects. Each decision-making factor includes one or more sub-factors within which future climate uncertainty may be explored; the modeling of stormwater behaviour (technical factor), investigation of regional climate (physiographic/climatic factor), delineation of risk factors associated with reuse projects (legislative and social factor), and investigation of maintenance/follow-up costs (economic factor) all allow the decision-maker to investigate the role of future uncertainty in reuse projects.

Another framework limitation is that it does not present municipalities with a means to select between competing sites for reuse implementation. Currently, the framework depends upon the continuous iteration between inputs (decision-making factors) and outputs (reuse system design) to reach a decision on optimal reuse system configuration and design for a given project site. However, if a municipality is trying to determine the most favourable location for reuse implementation, then the current configuration of the decision-making framework must be applied separately to each site, with no means for the municipality to decide upon which site is best from an economic, environmental, social, and technical perspective. Including a comparison tool within the framework to determine the most optimal site for implementation is a potential area of future work.

Finally, due to the fact that the decision-making framework has yet to be applied to real projects, there is no concrete data validating its performance. However, the validation methods presented in Subsection 4.1 present decision-makers with a starting point for documenting the performance of the framework. Ultimately, the objective of the validation methods is to provide a basis for building a database of municipal framework applications.

4.4 Recommendations for Future Work

The decision-making framework can be made more robust through the addition of several features. As municipalities begin to adopt the framework in the future, it will be necessary to elicit their feedback and use it to develop a more user-friendly version of the framework. In addition, user feedback and application of the validation methods will help identify specific framework components which could benefit from the incorporation of additional information or instructions. For example, if feedback suggests that the delineation of risk factors associated with reuse projects consistently presents a hurdle for municipalities, then this sub-factor will be updated to include information on potential methods for statistical and/or model-based risk identification used in past reuse projects.

The decision-making framework has been constructed such that future alterations may be easily completed. Currently, the framework is two-tier, with two flowcharts guiding the user towards a reuse implementation decision. Future versions of the framework may include additional flowcharts to guide users through the specific decision-making sub-factors. For example, monitoring of key stormwater parameters is a technical sub-factor which may benefit from additional guidance on the design of a stormwater monitoring program. In addition, future versions of the framework may include additional optimization tools and statistical analysis techniques, such as a strategic method (e.g. decision-making matrix) for deciding amongst competing sites for stormwater reuse implementation.

4.5 Summary

This chapter provided a description of two potential validation methods for the decision-making framework: (1) using sustainable development indicators, and (2) using the guiding principles which directed initial framework development. The chapter also used a case study site located in southern Ontario to demonstrate how the framework may be applied, with sample tasks which may be undertaken to investigate each decision-making factor. Lastly, framework limitations and recommendations for future work are discussed. Ultimately, the current configuration of the decision-making framework encourages future modifications and additions with increasing municipal adoption and user feedback.

4.6 References

AECOM Canada Ltd. (2012). Municipal Class Environmental Study Report for 'Subject Site X' [confidential report].

Chocat, B., Ashley, R., Marsalek, J., Matos, M., Rauch, W., Schilling, W., & Urbonas, B. (2007). Toward the sustainable management of urban storm-water. Indoor and Built Environment, 273-285.

Ministry of the Environment (2003). Understanding Stormwater Management: An Introduction to Stormwater Management Planning and Design. Retrieved from Ontario MOE: http://www.ene.gov.on.ca/stdprodconsume/groups/lr/@ene/@resources/documents/resource/std01_079720.pdf

Nanos, M. (2013). Thesis: A Feasibility Analysis of Site-Level Stormwater Reuse for Commercial Developments in Canada. Queen's University, Kingston, Ontario, Canada.

Palme, U. (2010). On prerequisites for the application of sustainable development indicators in urban water management. Sustainability, 92-116.

United Nations World Commission on Environment and Development (WCED). (1987). Our Common Future. Oxford University Press.

Upadhyaya, J., & Moore, G. (2012). Sustainability indicators for wastewater reuse systems and their application to two small systems in rural Victoria, Australia. Canadian Journal of Civil Engineering, 674-688.

WeatherSpark. (2012). Average Weather for [Municipality], Ontario, Canada. Retrieved January 2014, from http://weatherspark.com/averages.

Zhen, J., Shoemaker, L., Riverson, J., Alvi, K., & Cheng, M. (2006). BMP analysis system for watershed-based stormwater management. Journal of Environmental Science and Health Part A, 1391-1403.

Chapter 5

Summary and Conclusions

Several authors highlight the potential of stormwater reuse to decrease the ecological footprint of urban areas and better manage water resources. However, for this potential to be realized, it is critical that stormwater reuse is strategically incorporated into urban water resources planning and management. As a result, it is crucial to not only incorporate technical, physiographic, climatic, economic, legislative, and social factors into stormwater reuse applications, but also to integrate the applications themselves into the overall urban water cycle. The proper incorporation of stormwater reuse systems into local and regional water cycles is a critical factor in maintaining necessary environmental flows and ensuring flood protection needs are met.

The stormwater reuse decision-making framework presented in this thesis is intended to aid Canadian municipalities in the adoption of stormwater reuse. The framework, composed of a two-part flowchart, emphasizes the multi-faceted nature of stormwater reuse. It guides the decision-maker through a holistic consideration of factors which may influence the planning and implementation stages of stormwater reuse. The decision-making factors depicted in the framework include the following: (1) technical factors (stormwater reuse characterization and reuse system design); (2) physiographic and climatic factors (climate; land; hydrology; topography; soils); (3) legislative and social factors; (4) economic factors.

The following research contributions have been made by the research presented in this thesis:

1. Development of a multi-category decision-making framework for Canadian municipalities which incorporates technical, physiographic, climatic, legislative, social, and economic factors potentially impacting stormwater reuse decisions;
2. Delineation of specific variables (i.e. sub-factors) which may impact stormwater reuse planning and implementation;
3. Determination of specific driver and barrier relationships between reuse decision-making variables;

4. Presentation of a preliminary application of the framework to a case study in southeastern Ontario and discussion of potential framework performance assessment methods.

Currently, the scarcity of scientific literature documenting stormwater reuse applications makes it difficult to assess the long-term hydrologic impacts of stormwater reuse implementation. As a result, the role of reuse within the larger watershed management scheme needs to be better understood. In the meantime, it is important to recognize that stormwater reuse is a single piece of the stormwater management puzzle and thus must be strategically implemented along with other runoff management methods.