Performance Modeling and Simulation for Water Distribution and Wastewater Collection Networks

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Civil Engineering

Waterloo, Ontario, Canada, 2016

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Over the past decade many performance indicators have been developed for water and wastewater utilities. While existing performance indicators allow utilities to track performance over time and with respect to utility set objectives, they do not allow comparison of a utility's performance with respect to another utility. To overcome this deficiency in performance indicators, a series of water and wastewater benchmarking performance indicators are developed that are aggregated into 1) infrastructure, 2) socio-political, and 3) financial. These indicators are normalized and time-integrated to capture the cumulative adjustments made by the utility. A functional demonstration for validation is presented using the Rehan et al. (2013) system dynamics model for three Ontario water utilities with a pay-as-you-go financing strategy to benchmark, forecast and graphically compare each utility's performance over a 100-year benchmarking period. Results demonstrate that different water utilities can be benchmarked against each other using the benchmarking performance indicators. This will allow water utilities' management practices to be compared locally, regionally and nationally regardless of the utility size (small, medium or large) to identify opportunities for improvements and best practices.

An implementation framework for water distribution and wastewater collection networks asset management strategy is then developed comprising of three decision-making layers: 1) "visions & values", 2) "function", and 3) "performance". The asset management strategy framework is then implemented and validated through demonstration of functionality and value by using data from three utilities in Ontario, Canada. Results indicate that the three utilities studied achieve the strategic targets established in the visions & values layer over the benchmarking period (100 years).

A causal loop diagram for integrated asset management of water distribution and wastewater collection networks is presented. The causal loop diagram lays out the connection points and identifies the interacting feedback loops that exist among the integrated system components. The causal loop diagram is then translated into a system dynamics model comprised of integrated infrastructure, finance and socio-political sectors. The model data requirements and specific tests and procedures to validate the integrated system dynamics model are presented. The integrated model is implemented for a case study of a medium-sized Canadian municipality. The result indicates that the financial capacity to pay for capital and operational expenditures increases due to the integration of

the financial resources of water and wastewater utilities and thus improves the integrated levels of service.

In practice, water utilities' stakeholders can use the benchmarking performance indicators and asset management models developed in this research to negotiate and enact meaningful strategic targets and policy levers that lead to the sustainable asset management of the water distribution and wastewater collection networks over the life cycle of assets.

Acknowledgements

"In the Name of Allah, the Most Beneficent, the Most Merciful"

I would like to express my sincere gratitude and deepest appreciation to my supervisors Dr. Mark Knight and Dr. Carl Haas for their kind advice and exceptional mentorship throughout my PhD program. This research truly benefited from their constant encouragement and support of my ideas. My committee member, Dr. Andre Unger, has always been generous with his availability and has committed long hours reviewing my work with me and providing valuable guidance. I offer my sincerest gratitude to Dr. Andre Unger. I am also thankful to Dr. Bryan Tolson and Dr. Mohammad Kohandel my other committee members, for their review of my research proposal, offering insightful comments, and reviewing this thesis. It is a privilege to have Dr. Dragan Savic as my External Examiner and review my thesis for which I am highly grateful.

My studies have been made possible through the financial support of the Natural Sciences and Engineering Research Council of Canada-Doctoral Scholarship, University of Waterloo President Scholarship, and research grants of Dr. Mark Knight, Dr. Carl Haas and Dr. Andre Unger.

I am fortunate to have Dr. Rizwan Younis, Mr. Hadi Ganjidoost, Mr. Hamed Mohammadi Fardi, Mr. Amir Riahi, Mrs. Atefeh Shadpour, Mr. Robert Enouy, Mrs. Sevda Peygane, and Mr. Brendan Shapton as colleagues. Their friendship made my years at the University of Waterloo a most pleasurable experience. I would like to thank Dr. Rashid Rehan and Ms. Alice Seviora who over the years have become highly regarded friends.

I would also like to acknowledge the City of Waterloo, City of Cambridge and the City of Niagara Falls for making available their data for this research. Many staff members in both the cities, especially Ms. Denise McGoldrick, Mr. Michael Hausser, and Mr. Kent Schachowskoj, despite their hectic schedules, found time to meet and discuss my research and offer useful insights.

I would like to express my special gratitude work to my dear parents for their constant love, support and prayer, encouragement and for all of their warmth and care. My heartfelt gratitude goes to my beloved wife for her love, companionship and patient throughout our amazing journey.

Dedication

To my beloved wife

Fatemeh

,

My parents

for their continuous support

&

My little angel

Tasnim

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Chapter 1
Introduction

1.1 Background

Benchmarking is useful for water utilities to understand the network's performance, identify data gaps in performance, prioritize areas for improvement, and pursue the best management strategy to achieve improvements over the life-cycle of the infrastructure. MPMP (2007) indicates that "municipal decision-makers want to be efficient and deliver value for local services". This indicates a need to understand simultaneously the current and future behavior of the system to assist water utilities stakeholders to track their own performance and to compare their results to other water utilities. The first step to begin benchmarking starts by defining the performance indicators that are well-defined, understandable and meaningful to decision makers (FCM and NRC 2002). Over the past decade, many performance indicators and benchmarking guidelines have been developed worldwide to enable utilities to track their performance (FCM and NRC 2002; Alegre 2006; MPMP 2007; AWWA 2008; EPA 2008; OMBI 2012; NWC 2012; OFWAT 2012; Danilenko et al. 2014; AECOM 2015; Van den Berg and Danilenko 2011). Benchmarking can be used to re-examine the asset management strategies of a water utility in order to improve the water utility's levels of service over the life cycle of assets.

The Ontario Water Opportunities and Water Conservation Act (Government of Ontario 2010) recognizes the requirement of financially sustainable plans for water and wastewater systems. In addition, it requires plans for asset management of physical infrastructure, water conservation, and risk assessment and mitigation (Rehan et al. 2011). Thus, a municipality that seeks to sustain its aging water infrastructure systems with limited financial resources requires an asset management plan. ISO 55000 (ISO 2014), PAS 55 (PAS 2008), Uddin et al. (2013), Grigg (2012), EPA (2011), Falls et al. (2001), and TAC (1999) provide a number of definitions and guidelines for asset management. A common theme in most of the definitions is the emphasis on use of limited resources in an efficient and sustainable manner. PAS (2008) offers a useful definition as "asset management is the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their lifecycles for the purposes of achieving its

organizational strategic plan". It is argued that businesses have been able to increase their performance through adopting a systematic asset management approach (Woodhouse 2010).

Efforts have been made to develop decision-support tools using system dynamics (SD) modeling for asset management of water distribution and wastewater collection networks (Rehan et al. 2011; Rehan et al. 2013; Rehan et al. 2014a). These SD models were also implemented for strategic asset management of water distribution network (Rehan et al. 2015) and wastewater collection network (Rehan et al. 2014b). They are complimentary to and facilitate benchmarking for water and wastewater infrastructure asset management.

Environment Canada (2004) defines the water infrastructure system as comprised of "water treatment plants that purify our water, the water mains in the ground that transport water, and the towers and reservoirs that store water. The term includes the sewer pipes that carry away wastewater and the sewage treatment plants that treat wastewater before returning it to the environment …". Water distribution and wastewater collection systems are placed adjacent to each other, so deterioration in one can affect the infrastructure, socio-political and financial aspects of the other system. The volume of total sewage treated depends upon the total sewage generated and infiltration to the sewer pipes. Deterioration in water mains can increase the breakage rate and consequently increase leakage in water mains. Water main leakage could be a significant source of infiltration to a nearby sewer. Besides infiltration, leaking water might causes movement of soil particles around a sewer, resulting in loss of support and consequent damage to the sewer pipes. Water leakage also requires supplying more water than required to meet customers' needs. Exfiltration from a wastewater pipe can contaminate ground water which might be a source of supply for the water distribution system. Increased sewer infiltration means higher volume of sewage treated and higher treatment costs. Rehan et al. (2013) argued that Ontario's Ministry of Environment (MOE 2007) identifies the inter-relationship between water and wastewater infrastructure systems, and encourages municipalities to plan these systems in an integrated approach. For instance, an integrated asset management strategy increases the utility's available cash for water or wastewater infrastructure capital works due to the integration of the water and wastewater utilities' financial resources.

1.2 Problem Statement and Motivation

There have been considerable and well-documented concerns about the performance indicators for water utilities around the world as noted in the previous section. Unlike useful related performance indicators (MPMP 2007; OMBI 2012; AECOM 2015), current water utilities performance indicators (PI's) were developed to track a utility's performance over time and were not developed to compare different utilities' performance. To allow water utilities with different attributes, such as: pipe inventories (materials, condition and length); customer characteristics (population, density, consumption and conservation patterns); and, financial characteristics (allowable fee-hike rate, water fee, funds), to benchmark their asset management and financial position relative to one another, a set of benchmarking performance indicators (BPI's) are developed that are normalized and time-integrated and conform to the four broadly accepted efficacious themes of strategic target, policy lever, sustainability, and life cycle. These BPI's are presented in Chapter 2 of this thesis.

System dynamics was developed by Forrester (1958) to model complex systems. Rehan et al. (2011; 2013; 2014a) developed a first known system dynamics model that represents the complex interactions and feedback loops that exist among physical, finance and customers sectors of urban water distribution and wastewater collection systems and demonstrated that these are complex systems. Moreover, in separate studies, Rehan et al. (2014b; 2015) implemented their models for a synthesized utility data set. A review of Rehan et al. (2013; 2014a; 2014b; 2015) SD models for strategic asset management of water distribution and wastewater collection networks indicates some limitations associated with their models such as incomplete specification of fixed vs. variable revenue streams, and offers a unique opportunity for further research. An advanced system dynamics model is needed for each water distribution and wastewater collection network to improve deficiencies associated with the Rehan et al. (2013; 2014a) SD models.

According to Grigg (2009) the concepts of integration of water and wastewater infrastructure management systems were introduced as early as 1917. Katko et al. (2010) indicate that the concepts of integrating water and wastewater infrastructure are familiar, but the idea as a whole has not been fully embraced. A review of asset management models, decision support systems, and application of system dynamics to water distribution and wastewater collection networks reveals gaps in the existing body of knowledge. It indicates that the current asset management models are applied either to water distribution or wastewater collection systems. The dynamic behavior of water distribution and wastewater collection

systems in an integrated approach has not been studied. To properly understand the system behavior, a holistic integrated asset management framework is needed that integrate infrastructure, socio-political and financial sectors of water distribution and wastewater collection networks.

1.3 Research Objectives

The overall goal of this research is to present a framework for benchmarking and asset management of water distribution and wastewater collection networks. This goal is achieved by pursuing the following specific research objectives:

1. Develop benchmarking performance indicators for water distribution and wastewater collection networks to benchmark and compare utilities' performances regardless of the utility size (small, medium or large).
2. Identify key variables and required data to develop and implement benchmarking performance indicators.
3. Develop an architecture to implement the-three interconnected decision-making layers for asset management strategy of water distribution and wastewater collection network.
4. Continue the development and advancements of the Rehan et al. (2013; 2014a; 2014b; 2015) system dynamics models.
5. Graphically illustrate the interconnections and feedback loops that exist among various components of the integrated water distribution and wastewater collection systems using causal loop diagrams.
6. Develop a decision support model for integrated asset management of municipal water distribution and wastewater collection networks that integrate their respective infrastructure, socio-political and financial sectors using system dynamics modeling. The model should include infrastructure, socio-political and financial policy levers to allow the water utility's stakeholders to peruse decision-making policies for improvements and best practices.

1.4 Thesis Organization

This thesis is organized in an integrated-article format – that is, each of Chapters 2 to 5 addresses one or several of the above listed research objectives. Figure 1.1 presents a graphical summary of the remainder of thesis chapters and the main research tasks performed in each of those chapters.

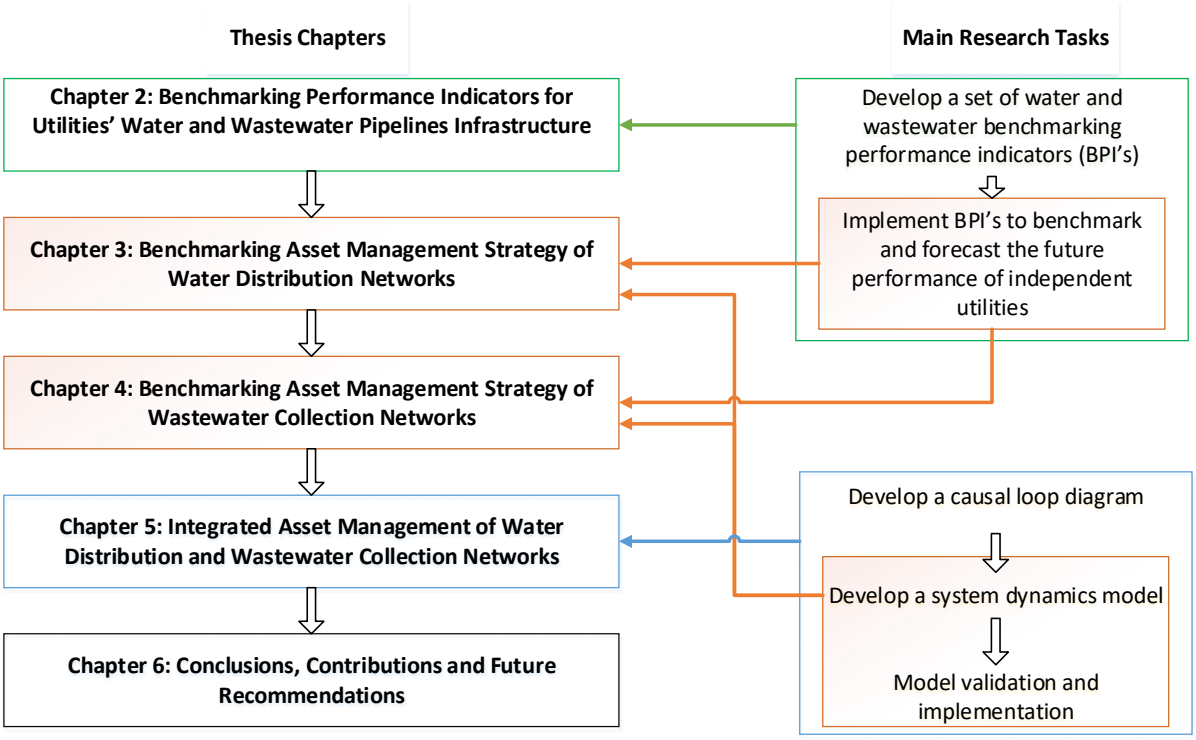


Figure 1.1: Flow chart of thesis chapters and research tasks.

Chapter 1Chapter 2 develops a set of normalized and time-integrated "benchmarking performance Indicators" for sustainable long-term management of water distribution and wastewater collection networks. A subset of the benchmarking performance indicators are used to benchmark and forecast the future performance behaviour of the water distribution networks for three water utilities in Ontario, Canada. The benefits of using the benchmarking performance indicators for water utilities' stakeholders are discussed.

In Chapter 3, development of an implementation framework for asset management strategy of water distribution network is presented that use 1) an advanced system dynamics model to forecast the future behavior of the water distribution network, and 2) the entire set of benchmarking performance indicators developed in Chapter 2. A capital reserving financing strategy is considered over a 100-year benchmarking period to benchmark three water utilities' performance. The effect of desired cash reserve on two selected benchmarking performance indicators is also discussed.

Chapter 4 describes development of an implementation framework for asset management strategy of wastewater collection network. Using an advanced system dynamics model with a borrowing

management strategy, the entire set of benchmarking performance indicators for wastewater collection network developed in Chapter 2 are implemented to benchmark and compare three utilities performance over a 100-year benchmarking period. The effect of interest rate spread (i.e., interest rate in excess of risk free rate) on borrowing strategy is discussed. Trade-offs between borrowing versus no borrowing management strategies is also explored.

A detailed causal loop diagram and a system dynamics model for the integrated asset management of municipal water distribution and wastewater collection networks are presented in Chapter 5. Data requirements and policy levers for the integrated model are discussed. The specific test methods to validate the system dynamics model are also presented. The integrated asset management model is implemented using data from one utility in Southern Ontario, Canada to explore the impact of interconnections and feedback loops that exist among the integrated infrastructure, socio-political and financial sectors of water distribution and wastewater collection networks. A general summary of conclusions, original contributions to the state of knowledge, and directions for future research are presented in Chapter 6.

Chapter 2
Benchmarking Performance Indicators for Utilities' Water and Wastewater Pipelines Infrastructure

2.1 Overview

Over the past decade many performance indicators have been developed for water utilities to track their systems. This study proposes a set of normalized and time-integrated "benchmarking performance Indicators" for sustainable long-term management of water distribution and wastewater collection networks. The benchmarking performance indicators are aggregated into three categories: 1) infrastructure, 2) socio-political, and 3) financial. To demonstrate the use and value of the benchmarking performance indicators, a system dynamics model is used to present a case study for three water utilities in Southern Ontario, Canada. This study shows that the benchmarking performance indicators will allow water utilities, with different attributes (such as; number of customers, network pipe age profile, pipe material type, network size, and location) to benchmark the long-term variation in their performance with other utilities-regionally and nationally. Furthermore, the benchmarking performance indicators can be used to forecast the future behaviour of the system to peruse decision-making policies for improvements and best practices.

2.2 Introduction

Over the past 15 years many legislators, researchers and industry practitioners have developed performance indicators for water utilities (Alegre 2006; AWWA 2008). The first step for a utility to benchmark their performance, internally from year to year and additionally to other utilities, is to establish relevant performance indicators (PI's) that are uniformly applicable, understandable, and meaningful to all utilities and decision makers (FCM and NRC 2002). Performance indicators, also referred to as performance measures, are systems variables that measure the system effectiveness, reliability and cost. Berg (2010) defines effectiveness as the extent to which the water utility achieves its targets and efficiency in terms of established standards (state of being efficient).

This study reviews existing performance indicators that water utilities commonly use to benchmark their water distribution and wastewater collection systems within Canada and the United States. It then discusses the limitations of existing performance indicators that impede benchmarking between utilities

with reference to a variety disparate attributes, such as: customer base and their associated consumption and conservation behaviour; size and distribution of the network; inventory of pipe material types and age profiles; and, financial strategies to balance revenue with expenses. The objective of this work is to introduce benchmarking performance indicators (BPI's) that normalize these attributes and enable effective benchmarking between utilities regardless of the utility scale. These BPI's can be used to help water utilities to: identify data required for a performance comparison; understand the strengths and weakness of their past and current performance; and, forecast their future performance over the life cycle of the infrastructure. These BPI's conform to the established and ubiquitous concepts of: strategic targets, policy levers, sustainability, and life cycle. Furthermore, they are organized into three categories: infrastructure, socio-political, and financial.

The merits of the BPI's are illustrated using data and parameters from the water distribution systems of three water utilities within Southern Ontario, with 100-year infrastructure life-cycle forecasts obtained from (but not limited to the use of) the Rehan et al. (2013; 2015) system dynamics models. The results demonstrate the virtue of normalizing attributes from the infrastructure, socio-political, and financial sectors to enable effective benchmarking between utilities, and to understand the complexity of these systems. Additionally, these results also show how forecasting these BPI's enable a utility to demonstrate compliance with strategic targets and policy levers, and demonstrate long-term sustainability over the life cycle of the infrastructure system.

2.3 Literature Review

Previous benchmarking frameworks, initiatives and PI's have been developed worldwide to enable utilities to track their performance, identify data gaps, and prioritize areas for improvement (FCM and NRC 2002; Alegre 2006; MPMP 2007; AWWA 2008; EPA 2008; OMBI 2012; NWC 2012; OFWAT 2012; Danilenko et al. 2014; AECOM 2015). This section presents a review of benchmarking initiatives and PI's for water infrastructure in Canada and the United States, with a focus on those that pertain to water distribution and wastewater collection systems.

2.3.1 Benchmarking Initiatives and Performance Indicators in Canada as well as North America

The National Water and Wastewater Benchmarking Initiative (NWWBI) was established in 1997 (AECOM 2015) to address the need of Canadian municipalities to measure, monitor and benchmark their

water utility performance. The focus of the NWWBI is on water treatment and distribution systems, wastewater collection and treatment systems, and storm water management systems. The outcome of the NWWBI is to enable member utilities to identify opportunities for improvements and "best practices" (AECOM 2015). Table 2.1 itemizes a brief selection of NWWBI performance indicators that are relevant to water distribution and wastewater collection systems. Note that while some of the PI's are normalized, others are not. Even those that are normalized such as "total operating and maintenance cost per kilometre length of pipe" are simply instantaneous measures of system performance. They do not directly denote "time" and hence without modification do not facilitate a utility to demonstrate long-term sustainability over the life cycle of the infrastructure system. Additionally, a utility with greater urban densification resulting in more individuals accessing a given kilometre of pipe relative to another utility with a greater degree of urban sprawl may have identical values of total operating and maintenance cost per kilometre length of pipe. However, their performance could not be construed as being equivalent. Omission of population within the performance indicator does not give it clear meaning.

The Ontario Municipal Benchmarking Initiative (OMBI) measures, benchmarks and shares the performance data and operational practices of fifteen municipalities across thirty-seven service areas (OMBI 2012). Two of their objectives for using performance indicators are to determine: 1) efficient and effective water distribution and wastewater collection practices; and, 2) maintenance of adequate capacity for existing communities and future developments. Table 2.1 itemizes three OMBI indicators. Note the overlap between "the total cost of water distribution/wastewater collection per kilometre of pipe" and the first NWWBI performance indicator listed on the same table. Clearly the same issues identified above apply. Once again, imagine two cities with varying degrees of urban densification/sprawl but now with identical pipe condition and population. The city with greater urban densification would experience greater "litres of treated water per 100,000 population" relative to the city with more urban sprawl and hence pipe length per capita. The basis for this assertion is that the pipe condition is responsible for leakage and unbillable water. A longer pipe network would lead to more leakage.

The Municipal Performance Measurement Program (MPMP) was developed by the Ontario Ministry of Municipal Affairs and Housing to enable Ontario utilities to report their annual performance data in the Financial Information Return (MPMP 2007). Table 2.1 provides MPMP indicator operation costs per kilometre of wastewater/water main operating to measure network's operating costs efficiency. Effective January 1, 2015, the reporting requirement of Financial Information Return data ceased. The Ontario

Ministry of Municipal Affairs and Housing still encourages municipalities to independently report their performance data to the public to demonstrate service improvement (MPMP 2015).

The American Water Works Association introduced the first version of the Utility Quality Service Program in 2003, which is now known as QualServ (Lafferty and Lauer 2005). QualServ contains PI's for the organizational development, customer relations, business operations, and water operations of water utilities (AWWA 2008). Table 2.1 provides four QualServ PI's that demonstrate attributes relevant to the infrastructure, financial, and socio-political sectors of all utilities. For instance, "operations and maintenance cost ratio" further normalizes cost to the number of customer accounts and treated water. However, it does not normalize relative to the length of network. Other PI's such as "distribution system water loss" remain non-normalized.

The Water Research Foundation (WRF) developed an excel-based benchmarking tool to effectively manage water utilities (WRF 2014). The WRF benchmarking approach identifies "Primer" practice areas to support the ten attributes within EPA's Effective Utility Management (WRF 2014): 1) product quality, 2) customer satisfaction, 3) employee and leadership development, 4) operational optimization, 5) financial viability, 6) infrastructure stability, 7) operational resiliency, 8) community sustainability, 9) water resource adequacy, and 10) stakeholder understanding and support. Furthermore, it improves the various QualServ business systems areas and its associated metrics. The WRF benchmarking tool enables water utilities to assess their own performance but does not provide cross-utility comparisons (WRF 2014). In keeping with this work, there is an intent to quantify concepts of: strategic targets, policy levers, sustainability, and life cycle. However, the methodology is not strongly articulated in the PI's itemized in Table 2.1.

Table 2.1: Selected Performance Indicators

Initiative	Performance Indicator	What Do They Measure	Unit	Normalized
The National Water and Wastewater Benchmarking Initiative (AECOM 2015)	Total operating and maintenance cost per kilometre (km) length of pipe	Cost effectiveness	$[\$/km]$	Yes
	Number (#) of water/wastewater related customer complaints per 1,000 people served	Customer satisfaction	$[\#/c]$ $c = capi$	Yes
	Non-revenue water in litre (L) per service connection (sc) per day (d)	System management /condition/reliability	$[L/sc/d]$	Yes
	% of inoperable or Leaking Valves	System reliability	[%]	Yes
	5-year running average capital reinvestment replacement value	Level of infrastructure reinvestment	[$]	No
	% of main length replaced	Level of infrastructure reinvestment	[%]	Yes
The Ontario Municipal Benchmarking Initiative (OMBI 2012)	The total cost of water distribution/wastewater collection per kilometre of pipe	Cost efficiency	$[\$/km]$	Yes
	Mega litres (ML) of treated water per 100,000 population	Service level	$[ML/c]$	Yes
	Average age of water/wastewater pipe	Customer service	$[year]$	Yes
The Municipal Performance Measurement Program (MPMP 2007)	Operation costs per kilometre of wastewater/water main	Operating costs efficiency	$[\$/km]$	Yes

The American Water Works Association (Lafferty and Lauer 2005)	Operations and maintenance cost ratio	Ratio between the cost of operations and maintenance and number of accounts per millions of gallons of produced water	[$ $/account$ $/m^3$]	Yes
	Distribution system water loss	Unaccounted water	$[m^3]$	No
	Return on assets	Financial effectiveness of the utility	[$]	No
	Residential cost of water service	Average residential water bill amount for one month of service	$[\$/account]$	Yes
The Water Research Foundation (WRF 2014)	Weighted average age of water/wastewater pipe	Infrastructure stability	$[year]$	Yes
	Level of asset condition information	Infrastructure stability	$[-]$	No
	Extent to which the critical assets are identified	Infrastructure stability	$[-]$	No
	Appropriateness of balance of capital spending between debt & equity expenditures	Financial viability	[%]	Yes
	Per capita consumption	Water resource adequacy	$[gpcd, lpcd]$*	Yes
	Water service affordability	Community sustainability	[%]	Yes

* $gpcd =$ gallons per capita per day; $lpcd =$ litres per capita per day.

2.4 Development of Benchmarking Performance Indicators for Water and Wastewater Pipelines

To address the shortcomings of the existing performance indicators reviewed above, this section introduces benchmarking performance indicators (BPI's) to further enable water utilities to compare and contrast their performance against one another, and against their own strategic targets. Strategic targets

are global assessments of abstract goals or ideals (FCM and NRC 2002), such as: “revenues equal expenses”; or, a more concrete “rehabilitate 1% of the network’s length every year”. Figure 2.1 illustrates the proposed framework for developing and organizing the benchmarking performance indicators. The framework conforms to the concepts of: strategic targets, policy levers, sustainability, and life cycle. Next, the performance indicators are grouped into three categories including: (1) infrastructure, (2) socio-political, and (3) financial.

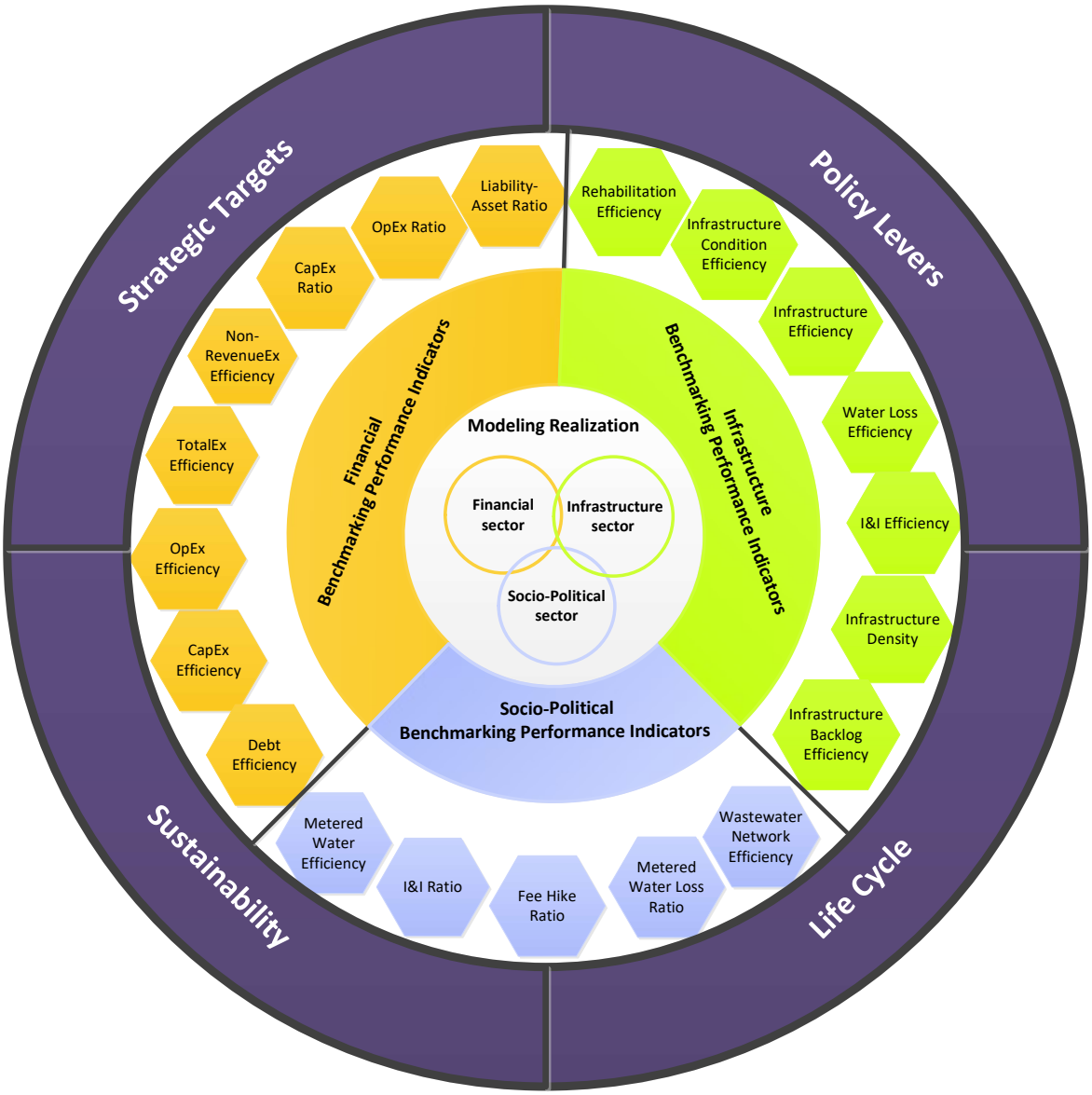


Figure 2.1: Framework of the benchmarking performance indicators for water and wastewater pipelines.

Table 2.2 provides a detailed description of the key variables that are used to develop the benchmarking performance indicators shown in Figure 2.1. Unlike existing PI's, all variables are time-varying to facilitate forecasting the BPI's over the asset life cycle. Those denoted as $x(t)$ track system behaviour instantaneously at time "t", while those denoted as $X(T)$ are time integrated, as noted in Equation 2.1, to capture aggregate system behaviour over the benchmarking period "T":

$$X(T) = \sum_{t=0}^{T} x(t) \tag{2.1}$$

where, T is the term of benchmarking period in years (and is representative of the life cycle of the asset) and t is the time with constraint of $0 \leq t \leq T$.

Aggregate system behaviour is used to capture the sum of all actions taken by the utility to manage the infrastructure over T. The benchmarking period (T) can be the systems life cycle i.e., 50 to 100 years, or the typical budget period of 5 to 10 years. Key variables from Table 2.2 are then normalized within and across the infrastructure, socio-political, and financial sectors to generate the BPI's in Table 2.3 to Table 2.5. These BPI's can then be used to explicate the complex interactions and feedback loops that exist among the sectors, and to facilitate the comparison of water utilities' performance regardless of their scale (small, medium or large). Additionally, the BPI's can be used to forecast future behaviour of the system by time integration over the benchmarking period. This enables a utility to determine long-term solutions that achieve sustainable performance targets and objectives.

Table 2.2: Key variables for constructing benchmarking performance indicators.

Variable	**Unit**	**Benchmarking Calculation**	**Unit**
Fee hike $FH(t)$	[%]	—	—
Rehabilitation rate $Rr(t)$	[%]	—	—
Network condition $NC(t)$	$[ICG]\ for\ WWC$ $[yr]\ for\ WD$	—	—
Population $P(t)$	$[c]$	$\bar{P}(T) = \sum_{t=1}^{T} P(t) \times \frac{\Delta t}{T}$	$[c]$

Network length $NL(t)$	$[m]$	$\overline{NL}(T) = \sum_{t=1}^{T} NL(t) \times \frac{\Delta t}{T}$	$[m]$
Fund balance $FB(t)$	[$]	$FB(T) = \sum_{t=0}^{T} FB(t)$	[$]
Debt $D(t)$	[$]	$D(T) = \sum_{t=0}^{T} D(t)$	[$]
Capital Reserve $CR(t)$	[$]	$CR(T) = \sum_{t=0}^{T} CR(t)$	[$]
Network asset value $NAV(t)$	[$]	$NAV(T) = \sum_{t=0}^{T} NAV(t)$	[$]
Wastewater treated $WWT(t)$	$\left[\frac{m^3}{d}\right]$	$WWT(T) = \sum_{t=0}^{T} \dot{WWT}(t) \times \Delta t$	$[m^3]$
Supplied water $SW(t)$	$\left[\frac{m^3}{d}\right]$	$SW(T) = \sum_{t=0}^{T} \dot{SW}(t) \times \Delta t$	$[m^3]$
Metered Water $MW(t)$	$\left[\frac{m^3}{d}\right]$	$MW(T) = \sum_{t=0}^{T} \dot{MW}(t) \times \Delta t$	$[m^3]$
Water loss $WL(t)$	$\left[\frac{m^3}{d}\right]$	$WL(T) = \sum_{t=0}^{T} \dot{WL}(t) \times \Delta t$	$[m^3]$

Inflow and Infiltration $I\&I(t)$	$\left[\frac{m^3}{d}\right]$	$I\&I(T) = \sum_{t=0}^{T} \dot{I\&I}(t) \times \Delta t$	$[m^3]$
Revenue $RV(t)$	$\left[\frac{\$}{yr}\right]$	$RV(T) = \sum_{t=0}^{T} \dot{RV}(t) \times \Delta t$	[$]
Total expenditures $TotalEx(t)$	$\left[\frac{\$}{yr}\right]$	$TotalEx(T) = \sum_{t=0}^{T} \dot{TotalEx}(t) \times \Delta t$	[$]
Inflow and Infiltration expenditures $I\&IEx(t)$	$\left[\frac{\$}{yr}\right]$	$I\&IEx(T) = \sum_{t=0}^{T} \dot{I\&IEx}(t) \times \Delta t$	[$]
Water loss expenditures $WLEx(t)$	$\left[\frac{\$}{yr}\right]$	$WLEx(T) = \sum_{t=0}^{T} \dot{WLEx}(t) \times \Delta t$	[$]
Capital expenditures $CapEx(t)$	$\left[\frac{\$}{yr}\right]$	$CapEx(T) = \sum_{t=0}^{T} \dot{CapEx}(t) \times \Delta t$	[$]
Operational expenditures $OpEx(t)$	$\left[\frac{\$}{yr}\right]$	$OpEx(T) = \sum_{t=0}^{T} \dot{OpEx}(t) \times \Delta t$	[$]
Maintenance expenditures $MaintEx(t)$	$\left[\frac{\$}{yr}\right]$	$MaintEx(T) = \sum_{t=0}^{T} \dot{MaintEx}(t) \times \Delta t$	[$]
Interest expenditures $IntEx(t)$	$\left[\frac{\$}{yr}\right]$	$IntEx(T) = \sum_{t=0}^{T} \dot{IntEx}(t) \times \Delta t$	[$]

Wastewater treated expenditures $WWTEx(t)$	$\left[\frac{\$}{yr}\right]$	$WWTEx(T) = \sum_{t=0}^{T} \dot{WWTEx}(t) \times \Delta t$	[$]
Supplied water expenditures $SWEx(t)$	$\left[\frac{\$}{yr}\right]$	$SWEx(T) = \sum_{t=0}^{T} \dot{SWEx}(t) \times \Delta t$	[$]
Metered water expenditures $MWEx(t)$	$\left[\frac{\$}{yr}\right]$	$MWEx(T) = \sum_{t=0}^{T} \dot{MWEx}(t) \times \Delta t$	[$]

Notes: t = time; ICG = internal condition grade; c = capita; d = day $[\frac{1}{365} yr]$; m = meter; T = the benchmarking period in years; Δt = time step; yr = year; WD = water distribution; WWC = wastewater collection.

2.4.1 Infrastructure Performance Indicators

Benchmarking performance indicators specific to the water distribution (WD) and wastewater collection (WWC) infrastructure are itemized in Table 2.3. Infrastructure efficiency and infrastructure density are the ratio of the network length to population and service area, respectively. Infrastructure backlog and infrastructure condition efficiency focus on the total length of WD and WWC pipes that have exceeded their design life $\mathbb{D}$ for WD or alternatively are in the worst internal condition grade for WWC. The rehabilitation efficiency is a ratio of the actual rehabilitation rate to target rehabilitation. The target rehabilitation rate (or preferred rehabilitation rate) is considered as a policy lever in the Rehan et al. (2014b; 2015) models. Finally, the last two BPI's in Table 2.3 are the ratio of water loss for WD or inflow and infiltration for WWC, normalized by the network length, population served, and benchmarking period.

Table 2.3**:** Infrastructure performance indicators.

Sector	Benchmarking Performance Indicator	Description	Calculation	Unit
WD/WWC	**Infrastructure Efficiency**	Total network length (NL) divided by population (P) served by utility.	$[\frac{\sum_i NL(t)}{P(t)}]$	$[m/c]$
WD/WWC	**Infrastructure Density**	Total network length divided by utility serviced area (A).	$[\frac{\sum_i NL(t)}{A(t)}]$	$[m/m^2]$
WD	**Infrastructure Backlog Efficiency**	Length of pipes over design life $(\mathbb{D})$ divided by total network length.	$[\frac{\sum_{NL>\mathbb{D}}^{i} NL(t)}{\sum_i NL(t)}]$	$[m/m]$
WD	**Infrastructure Condition Efficiency**	Length of pipes over design life $(\mathbb{D})$ divided by population served by utility.	$[\frac{\sum_{NL>\mathbb{D}}^{i} NL(t)}{P(t)}]$	$[m/c]$
WWC	**Infrastructure Backlog Efficiency**	Length of pipes in Internal condition grade (ICG) divided by total network length.	$[\frac{\sum_{ICG5i} NL(t)}{\sum_i NL(t)}]$	$[m/m]$

WWC	**Infrastructure Condition Efficiency**	Length of ICG 5 pipes divided by population served by utility.	$\left[\frac{\sum_{ICG5i} NL(t)}{P(t)}\right]$	$[m/c]$
WD/WWC	**Rehabilitation Efficiency**	Percentage of actual rehabilitation rate (Rr) to target rehabilitation rate per year.	$\left[\frac{Actual\ Rr(t)}{Target\ Rr(t)} \times 100\right]$	$[\%/yr]$
WD	**Water Loss Efficiency**	Water loss (WL) divided by total network length per population served by utility over the benchmarking period.	$[WL(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T) \div T]$	$[m^3/m\,/c/yr]$ or $[l/m\,/c/yr]$ or $[Ml/m\,/c/yr]$
WWC	***I*&*I* Efficiency**	Total volume of inflow and infiltration ($I\&I$) divided by total network length per population served by utility over the benchmarking period.	$[I\&I(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T) \div T]$	$[m^3/m\,/c/yr]$ or $[l/m\,/c/yr]$ or $[Ml/m\,/c/yr]$

Notes: WD = water distribution; WWC = wastewater collection; m = meter; c = capita; a = watermain age; i = type of pipe material; A = service area covered by a water utility; ICG = internal condition grade; yr = year.

2.4.2 Socio-Political Performance Indicators

Benchmarking performance indicators specific to the socio-political sector are itemized in Table 2.4. The fee hike ratio measures the ratio of the actual to the allowable fee-hike rates on the variable unit cost of water or wastewater, with the allowable fee-hike rate being a policy lever in the Rehan et al. (2014b; 2015) models. The rest of BPI's presented in Table 2.4 relate to the material balance of water within the distribution and collection network between the water and wastewater treatment plants, with metered water indicating the consumption behaviour of residents over the benchmarking period, as presented in Equation 2.2 for WD and Equation 2.3 for WWC:

$$MW(T) = SW(T) - WL(T) \quad (2.2)$$

Where, MW is metered water; SW is supplied water; WL is water loss, and:

$$MW(T) = WWT(T) - I\&I(T) + NCW(T) \quad (2.3)$$

where, MW is metered water; WWT is wastewater treated; $I\&I$ is inflow and infiltration; NCW is non consumptive water.

An increase in the water user fee will lead to a decrease in the average daily water demand per capita per day due to price elasticity of demand. Conservation of metered water may not be transmitted to the water treatment plants (as SW) or wastewater treatment plants (as WWT) depending on the condition of the network. Sustainability would minimize WL, $I\&I$ and NCW over the life cycle of the infrastructure.

Table 2.4: Socio-political performance indicators.

Sector	Benchmarking Performance Indicator	Description	Calculation	Unit
WD/WWC	**Fee Hike Ratio**	Percentage of current fee hike (FH) to allowable fee hike per year.	$\left[\frac{Current\ FH(t)}{Allowable\ FH(t)} \times 100\right]$	$[\%/yr]$
WD	**Metered Water Efficiency**	Ratio of supplied water (SW) to metered water (MW).	$[\frac{SW(T)}{MW(T)}]$	$[m^3/m^3]$
WD	**Metered Water Loss Ratio**	Ratio of water loss (WL) to metered water.	$[\frac{WL(T)}{MW(T)}]$	$[m^3/m^3]$
WWC	**Wastewater Network Efficiency**	Ratio of wastewater treated (WWT) to metered water.	$[\frac{WWT(T)}{MW(T)}]$	$[m^3/m^3]$
WWC	**(I&I) Ratio**	Ratio of inflow and infiltration to metered water.	$[\frac{I\&I(T)}{MW(T)}]$	$[m^3/m^3]$

Notes: m = meter; yr = year

2.4.3 Financial Performance Indicators

Benchmarking performance indicators specific to the financial sector are itemized in Table 2.5. The first ten of the thirteen BPI's are organized in terms of expenses generated by either the WD or WWC subcategories. Those that relate to WD are normalized by $SW(T)$ while those that relate to WWC are

normalized by $WWT(T)$. Given that revenue is generated by metered water, and the need for the utility to balance revenues with expenses, either one could be normalized by $MW(T)$ with appropriate adjustment by "metered water efficiency" or "wastewater network efficiency". All of these BPI's are further normalized by the length of the network and the population served. Total water distribution expenditures are the sum of operational, capital, and interest expenditures that are specific to the WD infrastructure given as:

$$TotalWDEx(T) = \sum_{t=0}^{T}[\dot{OpEx}(t) + \dot{CapEx}(t) + \dot{IntEx}(t)] \times \Delta t \quad (2.4)$$

where, $TotalWDEx$ is the total water distribution expenditures; $OpEx$ is the WD operational expenditures; $CapEx$ is the WD capital expenditures; $IntEx$ is the WD interest expenditures; t is the time; T is the benchmarking term; Δt is the discrete time interval across which system variables are evaluated.

In an analogous manner, total wastewater collection expenditures are given as:

$$TotalWWCEx(T) = \sum_{t=0}^{T}[\dot{OpEx}(t) + \dot{CapEx}(t) + \dot{IntEx}(t)] \times \Delta t \quad (2.5)$$

where, $TotalWWCEx$ is the total wastewater collection expenditures; $OpEx$ is the WWC operational expenditures; $CapEx$ is the WWC capital expenditures; $IntEx$ is the WWC interest expenditures.

The traditional and ubiquitous "liability asset ratio" BPI is quantified in terms of valuations pertinent to WD and WWC; debt, fund balance, cash reserve, cash required to rehabilitate/replace pipes reached their design life, and network asset value. The last two BPI's in Table 2.5 are the ratio of capital as well as operational expenditures to revenue generated by either WD or WWC.

Table 2.5: Financial performance indicators.

Sector	Benchmarking Performance Indicator	Description	Calculation	Unit
WD	**Water TotalEx Efficiency**	Total water distribution expenditures ($WDEx$) divided by supplied water (SW) over the benchmarking period (T) per network length (NL) per population(P).	$[TotalWDEx(T) \div SW(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T)]$ $TotalWDEx(T) = \sum_{t=0}^{T} (\dot{OpEx}(t) + \dot{CapEx}(t) + \dot{IntEx}(t)) \times \Delta t$ $OpEx(T) = MaintEx(T) + SWEx(T)$ $SWEx(T) = MWEx(T) + WLEx(T)$	$[\$/m^3/m/c]$
WD	**Water OpEx Efficiency**	Operational expenditures ($OpEx$) divided by supplied water over the benchmarking period per network length per population.	$[OpEx(T) \div SW(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$
WD	**Water CapEx Efficiency**	Capital expenditures ($CapEx$) divided by supplied water over the benchmarking period per network	$[CapEx(T) \div SW(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$

		length per population.		
WD	**Non-RevenueEx Efficiency**	Water loss expenditures ($WLEx$) divided by supplied water over the benchmarking period per network length per population.	$[WLEx(T) \div SW(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$
WD	**Water Debt Efficiency**	Debt (D) divided by supplied water over the benchmarking period per network length per population.	$[D(T) \div SW(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$
WWC	**Wastewater TotalEx Efficiency**	Total wastewater collection expenditures ($WWCEx$) divided by wastewater treated (WWT) over the benchmarking period per network length per population.	$[TotalWWCEx(T) \div WWT(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)]$ $TotalWWCEx(T) = \sum_{t=0}^{T} (\dot{OpEx}(t) + \dot{CapEx}(t) + \dot{IntEx}(t)) \times \Delta t$ $OpEx(T) = MaintEx(T) + WWTEx(T)$ $WWTEx(T) = MWEx(T) + I\&IEx(T)$	$[\$/m^3/m/c]$
WWC	**Wastewater OpEx Efficiency**	Operational expenditures ($OpEx$) divided by wastewater treated over the benchmarking	$[OpEx(T) \div WWT(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$

		period per network length per population.		
WWC	**Wastewater CapEx Efficiency**	Capital expenditures (CapEx) divided by wastewater treated over the benchmarking period per network length per population.	$[CapEx(T) \div WWT(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$
WWC	**Non-RevenueEx Efficiency**	Inflow and infiltration expenditures ($I\&IEx$) divided by wastewater treated over the benchmarking period per network length per population.	$[I\&IEx(T) \div\ WWT(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$
WWC	**Wastewater Debt Efficiency**	Debt divided by wastewater treated over the benchmarking period per network length per population.	$[D(T) \div WWT(T) \div \sum_i \overline{NL}\,(T) \div \bar{P}(T)]$	$[\$/m^3/m/c]$
WD/WWC	**Liability-Asset Ratio**	Percentage of liabilities to assets.	$\left[\frac{Liabilities\ (\$)}{Assets\ (\$)}\right] \times 100$ $= \left[\frac{D(T) + abs\big(neg.FB(T)\big) + CW(T)}{NAV(T) + \Big(if\ FB > 0, \big(FB(T) - CR(T)\big), CR(T)\Big)}\right] \times 100$	[%]

			CW = Cash required to rehabilitate/replace pipes reached their design life ($\mathbb{D}$)	
WD/WWC	**OpEx Ratio**	Ratio of operational expenditures ($OpEx$) to revenue (RV).	$\left[\frac{OpEx(T)}{RV(T)}\right]$	[\$/\$]
WD/WWC	**CapEx Ratio**	Ratio of capital expenditures ($CapEx$) to revenue (RV).	$\left[\frac{CapEx(T)}{RV(T)}\right]$	[\$/\$]

Notes: Δt = time step; $OpEx$ = operational expenditures; $CapEx$ = capital expenditures; $IntEx$ = interest expenditures; $MaintEx$ = maintenance expenditures; $SWEx$ = supplied water expenditures; $MWEx$ = metered water expenditures; $WLEx$ = water loss expenditures; $WWTEx$ = wastewater treated expenditures; $I\&IEx$ = inflow and infiltration expenditures; abs = absolute value; $neg.$ = Negative; CW = capital works; CR = capital reserve

2.5 Water Distribution Network Benchmarking Demonstration

A subset of the proposed BPI's are used to benchmark and forecast the future performance behaviour of the water distribution networks for three water utilities in Ontario, Canada (arbitrarily called X, Y and Z). The Rehan et al. (2013) system dynamics model for water distribution networks is used to forecast the future performance of each utility. Policy levers controlling the forecasting exercise are made as identical as possible between each utility under the assumption they will have similar preferences (due in part to their geographic proximity) for strategic targets, policy levers, sustainability, and life cycle. For this study a pay-as-you-go financing strategy is considered over a 100-year lifecycle of the infrastructure system representing the benchmarking period (T).

2.5.1 Input Data for the System Dynamics Model

Utilities X, Y and Z have 361, 501, and 450 kilometres of water distribution network pipes that serve 120,000, 130,000 and 83,000 customers, respectively. Their networks are comprised of pipes made of polyvinyl chloride (PVC), cast iron (CI), ductile iron (DI), and asbestos cement (AC). Initially, 5.5, 8.0 and 8.5 percent of their respective network lengths are more than 75 years old and beyond their design life $\mathbb{D}$. Note that $T > \mathbb{D}$ to accommodate an initial inventory of watermain pipes of varying ages, with the various pipe segments reaching $\mathbb{D}$ throughout T. Each water utility is assumed to be rehabilitating or replacing 1.3 percent of their water distribution networks length every year (policy lever). The allowable fee-hike rate (policy lever) on the unit cost of water needed to generate revenue to equal expenses thereby creating a zero fund balance (strategic target) under a pay-as-you-go financial strategy over the benchmarking period is: 9.5 percent per year for utilities X and Y; and, 11 percent per year for utility Z. Additionally, pipes beyond their design life are eliminated in 5 years (policy lever), and the percent of deteriorated pipes is targeted to be less than 5 percent of the total network length (policy lever).

The initial unit cost of water for utilities X, Y and Z is \$1.55, \$1.68 and \$0.92 per cubic meter, respectively. The current cost of water treatment is \$0.83 per cubic meter for utilities X and Y, and \$0.54 per cubic meter is used for utility Z. Initial residential water demand is 280 litre per capita per day ($lpcd$) for utilities X and Z, and 322 $lpcd$ for utility Y with additional demand from industrial and commercial accounts. The minimum residential water demand for the three utilities is assumed to be 150 $lpcd$. Price elasticity of water demand for the residential sector is assumed to be equal to -0.35 which is the average

of the range reported by Boland et al. (1984) and used by Rehan et al. (2011; 2014b; 2015).

The unit cost for rehabilitating pipes 75 to 100 years old is $600 per meter, while for pipes more than 100 years old it is set at $700 per meter. Total unit operation and maintenance costs are provided in Table 2.6, and leakage rate for each age group of pipes are provided in Table 2.7. Inflation rates are calculated in a manner identical to Rehan et al. (2015). For this analysis water treatment expenditures are excluded from the calculation of total expenditures.

Table 2.6: Total unit operation and maintenance cost for water distribution pipes in various age groups.

	Water Utility	**Material**	**Age group of pipes (years)**				
			0-24	**25-49**	**50-74**	**75-99**	**100-124**
Total unit O&M cost $[\$/m/yr]$	**X**	CI	7.73	8.22	11.69	36.06	207.40
		PVC	7.72	8.07	10.11	21.81	89.18
	Y	CI&DI	6.44	6.93	10.40	34.78	206.1
		PVC	6.43	6.78	8.2	20.52	87.90
	Z	CI&DI	6.99	7.48	10.95	35.33	206.66
		PVC	6.98	7.34	9.37	21.08	88.45
		AC	6.99	7.40	10.06	26.97	134.53

Table 2.7**:** Leakage rate of water distribution pipes in various age groups.

Applicable to all water utilities		**Age group of pipes (years)**				
		0-24	**25-49**	**50-74**	**75-99**	**100-124**
Leakage rate $[m^3/km/d]$	CI & DI	0.19	1.34	9.45	66.4	466.7
	PVC	0.17	1.0	5.75	33.1	190.5
	AC	0.18	1.16	7.37	46.89	298.19

2.5.2 Benchmarking Results

Table 2.8 itemizes the infrastructure efficiency BPI for each utility as $3.0, 3.85\ and\ 5.42\ m/c$ for utilities X, Y and Z, respectively. These values are constant over the benchmarking period because the water network length and population are assumed to be constant. Based on these values, utility Z has the highest

amount of urban sprawl and utility X has the lowest. A lower value suggests more efficient infrastructure usage and implies sustainability. Figure 2.2 presents four BPI's for the three utilities demonstrating: a) infrastructure condition efficiency; b) water TotalEx efficiency given by $TotalWDEx(T)$ in Equation 4; c) water loss efficiency; and, d) per capita water consumption (i.e., water demand) as noted in Table 2.1. The water demand PI, as shown in Figure 2.2, is time integrated over the 100-year benchmarking period T to be consistent with Equation 1 and the other three BPI's shown in Figure 2.2.

Table 2.8: Benchmarking performance indicator of the infrastructure efficiency.

Water Utility	**X**	**Y**	**Z**
Population $[c]$	120,000	130,000	83,000
Water main length $[m]$	361,000	501,000	450,000
Infrastructure Efficiency $[m/c]$	3.0	3.85	5.42

Figure 2.2a shows the infrastructure condition efficiency BPI, which is the fraction of pipes over 75 years old and beyond their design life, in units of metres per capita $[m/c]$. Infrastructure condition efficiency BPI starts with a value of $0.2, 0.3\ and\ 0.45\ m/c$ for utilities X, Y and Z, respectively. Generally, the three utilities show the same trend—a rapid linear decrease for the first 5 to 10 years, followed by linearly increasing trend to the end of benchmarking period. The initial decreasing trend is due to two policy levers: first, that each water utility is rehabilitating or replacing 1.3 percent of their water distribution networks length every year; and, second that no more than 5% of the network length can be aged beyond the design life. Thus, within 5 to 10 years all utilities generated enough revenue to support sufficient capital expenses to comply with the second policy lever. The post 10 year trend is due to ageing of the pipes within the network as it reaches a sustainable condition that is constrained by both of the above policy levers. At 100 years, the time integrated infrastructure condition efficiency BPI values are $0.08, 0.2\ and\ 0.12\ m/c$ for utilities X, Y and Z, respectively. These values are all lower than their initial values implying improvement in the systems condition due to the aggregate set of operation decisions made by each utility (due to enforcement of the policy levers) over the benchmarking period. Note that the three utilities show a small rapid increase (bump) in the infrastructure condition efficiency BPI between years 20 to 40. This bump is the result of a cohort of PVC pipes that were installed in the 1960's suddenly reaching their design life of 75 years of age. Finally, utility Y has the highest (worst) infrastructure condition efficiency value after 10 years. This is the result of utility Y having insufficient

capital works funds required to rehabilitate the fraction of highly deteriorated pipes. This funding shortfall is due to the maximum allowable fee-hike rate being set too low.

Figure 2.2b shows water TotalEx efficiency BPI which is a measure of a utilities' ability to efficiently recover revenue by billing for metered water, and is quantified by revenue for metered water divided by the supplied water from the water treatment plant, and further normalized by the water distribution network length and population [$\$ /m^3/m/c$]. Thus, a low value for water TotalEx efficiency BPI suggests efficient performance and implies sustainability. In general, this figure shows a relatively constant BPI value for the first 20 years then a generally increasing linear trend with some curvature. During the first 20 years the water TotalEx efficiency starts with a value of $\$0.22/m^3/m/c$ for water utilities X and Z, and $\$0.16/m^3/m/c$ for water utility Y. At the end of the benchmarking period the BPI values are $\$0.5, \$0.41$ and $\$0.52/m^3/m/c$ for utilities X, Y and Z, respectively. This increasing trend over time indicates that for all utilities the water TotalEx efficiency decreases over time. This trend is a function on two processes. Firstly, Rehan et al. (2013; 2015) show that inflation in operational and capital expenditures is greater than the risk free rate used to discount all expenses to present value, thereby making late-time operational and capital expenses comparatively more expensive. Secondly, as the network gradually ages over the benchmarking period, the unit cost of OpEx shown on Table 2.6 increases, thereby requiring the utility to obtain more revenue from metered water. The three utilities ultimately achieve similar behaviour over the entire benchmarking period with the spread in their water TotalEx efficiency never greater than approximately $\$0.11$ $m^3/m/c$. This spread persists due to an allowable fee-hike rate that permits each utility to have sufficient revenue to meet expenses over the benchmarking period. Figure 2.2b shows that utility Z consistently has the highest values of water TotalEx efficiency BPI over the benchmarking period compared to the other water utilities, and utility Y consistently has the lowest values. Thus, utility Y is deemed more efficient than utilities X and Z. As shown in Figure 2.2a, utility Z starts the benchmarking exercise with the highest fraction of deteriorated pipes. The need to eliminate these old pipes (policy lever) requires utility Z to have the greatest capital work expenditures and hence water TotalEx efficiency BPI. Utility Y achieves its low water TotalEx efficiency due to its low infrastructure efficiency BPI of 3.85 m/c compared to utility Z with a value of 5.42 m/c. Additionally, utility Y has completed significant water infrastructure renewal prior to this analysis resulting in the lower need for capital work expenditures compared to utility Z.

Figure 2.2c depicts water loss efficiency BPI quantified as the annual water loss through the water

distribution network per meter of network length per capita $[l/m\,/c/yr]$, with a low value implying efficient and sustainable network performance. Initial values for water utilities X, Y and Z are 0.036, 0.015 and 0.06 $l/m\,/c/yr$, respectively, and then rapidly decline to minimal and sustainable values by the end of the benchmarking period. As noted previously, utility Z initially has the oldest inventory of pipes and thus the highest initial leakage rate (see Table 2.7). In contrast, utility Y initially has the newest inventory of pipes and thus the lowest value water loss efficiency. The improvement in water loss efficiency for the three utilities over the benchmarking period is due to their efforts to remove water distribution pipe that is beyond its design life, as shown in Figure 2.2a.

Figure 2.2d shows the water demand BPI which measures users' average daily water consumption $[lpcd]$. It should be noted that this value is time integrated to show cumulative change in behaviour over the benchmarking period. The water demand BPI initially starts at 315, 345 and 350 $lpcd$ for water utilities X, Y and Z, respectively. Water demand then continuously declines for the three utilities over the benchmarking period to 183 $lpcd$ for utilities X and Z and 200 $lpcd$ for utility Y. The declining trend indicates water conversation due to water price increases and the price elasticity of demand function built into the Rehan et al. (2013; 2015) system dynamics model. Note that the initial water demand is calculated as the sum of residential, industrial and commercial water demand divided by the population under the assumption that all customers sectors experience the same price elasticity of water demand.

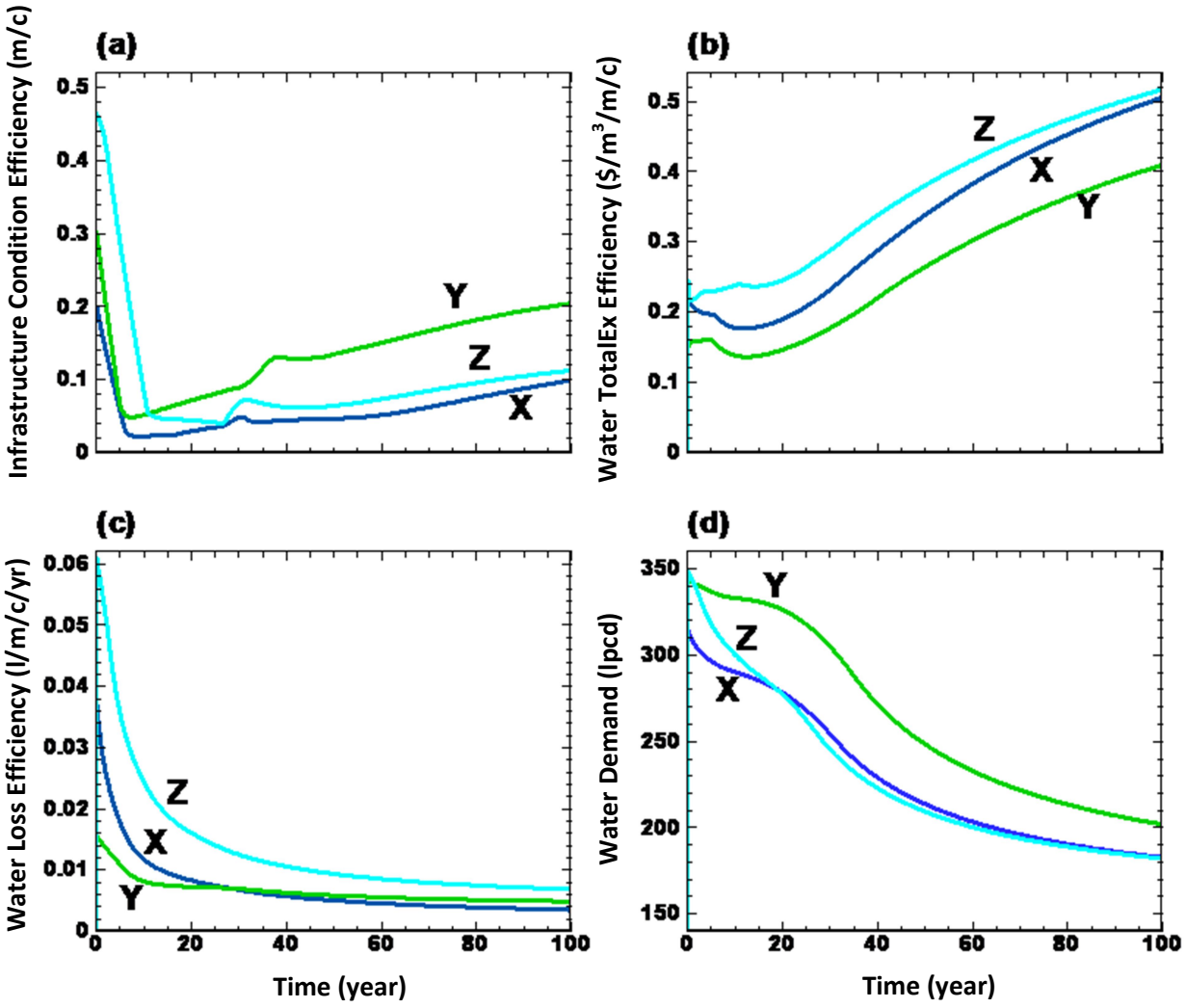


Figure 2.2: Benchmarking results over a 100-year forecasting period for utilities X, Y and Z.

2.5.3 Benchmarking Discussion

Rehan et al. (2011) demonstrated that water distribution and wastewater collection infrastructures are complex systems with multiple interconnections and feedback loops. This means that short-term behaviour of these systems is often contrary to their long-term response. The four presented BPI's demonstrate the complexity of water distribution system and how the BPI's can be used to benchmark utility's performance with different attributes – customer base, size of network, pipe material types and age profiles, etc. The application of the entire set of BPI's will allow a better understanding of the total system responses.

Utilities can use the benchmarking performance indicators to track performance and benchmark their performance with other utilities. The case study demonstrates that the three utilities can manage their assets across the same strategic target and policy levers controlling their targets. Due to differences in pipe inventories (materials, condition and length), customer characteristics (population, consumption and conservation patterns), and financial characteristics (allowable fee-hike rate, water fee, funds), all three water utilities show different behaviour over the benchmarking period. Utilities can implement different financial strategies (pay-as-you-go, borrowing, capital reserving, fixed and variable revenue) and decision-making policies for improvements and best practices, and meet strategic targets.

The BPI's introduced in this study provide a methodology to articulate the asset management and financial position of a water utility relative to its neighbours either locally, nationally, or even internationally. The effective regulation is then to set target values of relevant BPI's that drive a utility and its stakeholders to change its practices to be competitive with its neighbours. However, effective regulation should facilitate how the stakeholders enact this change under the premise that any given water utility knows its business best. The outcome of these BPI's is therefore to allow a water utility and its stakeholders to articulate acceptable objectives and paradigms, and then to negotiate and enact meaningful strategic targets and policy levers that lead to the sustainable management of the water distribution and wastewater collection systems.

The novelty and functionality of these BPI's have been validated as described in the preceding discussion. Assessments of over one dozen experts amongst the municipal partners that supported this research further support and validate the conclusion that these BPI's from an efficacious set of metrics for comparing utilities' past, present and potential future performance, which is critical for motivating management improvements and supporting strategic planning.

2.6 Conclusions

Based on this study, the following conclusions can be drawn:

1- Existing PI's do not denote "time", and many of them cannot be used to benchmark the performance of different utilities.

2- A series of normalized and time-integrated benchmarking performance indicators (BPI's) are developed that conform to the four themes of strategic target, policy lever, sustainability, and life

cycle.

3- BPI's will allow water utilities with different attributes, such as: pipe inventories (materials, condition and length); customer characteristics (population, consumption and conservation patterns); and, financial characteristics (allowable fee-hike rate, water fee, funds), to benchmark their asset management and financial position relative to one another.

4- BPI's can be used by various stakeholders to negotiate and enact meaningful strategic targets and policy levers that lead to the sustainable management of the water distribution system.

Chapter 3
Benchmarking Asset Management Strategy of Water Distribution Networks

3.1 Overview

This study develops an implementation framework for asset management strategy of water distribution networks comprised of three decision-making layers: 1) "visions & values", 2) "function", and 3) "performance". The asset management strategy framework is implemented and validated through demonstration of functionality and value by using data from three water utilities in Ontario, Canada. The visions and values layer is set to meet the needs of the water utilities' stakeholders. The function layer uses an advanced system dynamics model to simulate and forecast the future behavior of the system. Benchmarking performance indicators (i.e., the performance layer) use outputs of the advanced system dynamics model of this study to benchmark, compare, contrast and graphically illustrates the situation and performance of water utilities against each other regardless of their size. Results indicate that the three utilities studied can sustainably meet the strategic targets established in the visions and values layer of the asset management strategy over the benchmarking period. In addition, the results show that the forecasting feature of the function layer (i.e., advanced system dynamics model) enables water utilities to better understand the complex and dynamic behavior of the system and plan future actions required for sustainable long-term management of their respective systems. The impact of the desired cash reserve on infrastructure and financial benchmarking performance indicators is also investigated to explore the "optimal" combination of allowable fee-hike and rehabilitation rates by using the contour plots developed over the benchmarking period (100 years).

3.2 Introduction

Asset management is the "systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their lifecycles for the purposes of achieving its organizational strategic plan" (PAS 2008). It is argued that businesses have been able to increase their performance through adopting a systematic asset management approach (Woodhouse 2010).

Three interconnected decision-making layers for asset management strategy are identified as: (1) the outer circle (to find out 'Where do we want to go?'); (2) the inner circle (to find out 'How do we get there?'); and (3) the core circle (to find out 'How are we doing?') (Woodhouse 2010). The outer circle is the strategic level of decision-making looks at the visions and values of an organization; the inner circle looks at the organization itself to find out how it is structured and operates to achieve its vision and values (i.e., the outer circle); and finally the focal point of the decision-making (i.e., the core circle) monitors the achievement of the organization visions and reinforces its values (Woodhouse 2010).

Efforts have been made to develop decision-support tools using system dynamics (SD) modeling for asset management of water distribution and wastewater collection networks (Rehan et al. 2013; 2014a). These SD models are also implemented for water distribution network (Rehan et al. 2015) and wastewater collection network (Rehan et al. 2014b) to find out (1) 'Where do we want to go?' and (2) 'How do we get there?'. Chapter 2 develops a series of water and wastewater benchmarking performance indicators (BPI's) that will allow water utilities to benchmark and compare their management practices regardless of the utility scale. The BPI's enable water utilities to find out 'How they are/will be doing?', and hence pursue the best decision-making policies and management practices for sustainable long-term solutions. The case study presented in Chapter 2 is limited to only four BPI's. In addition, the Rehan et al. (2013; 2015) system dynamics models for strategic asset management of water distribution networks were restricted to some limitations as described in Section 3.4 of this Chapter.

This chapter develops an implementation framework for asset management strategy of water distribution networks comprised of three decision-making layers: "visions & values", "function", and "performance". The visions and values layer conform to the four themes of: strategic target, policy lever, sustainability, and life cycle, as noted in Chapter 2. For the function layer, this study improves the limitations associated with the Rehan et al. (2013; 2015) system dynamics models, as discussed in Section 3.4, to find out (1) 'How does the water utility achieve its visions and values?'. Then, the outputs of the improved SD model are used to apply the entire set of BPI's developed for the water distribution network to evaluate the total system's performance (i.e., the performance layer). Identifying stakeholders and their respective roles within this framework is integral to its implementation. In this context, utility managers and employees, regulators, potential private sectors investors, and the community are all identified as stakeholders. Utility managers and employees engage in all three levels of decision-making.

Community and regulators only involve in the visions and values layer of decision-making. And, investors' main concern is on the achievements of the utility (i.e., performance layer).

The function and merit of the proposed implementation framework for asset management strategy of water distribution networks is validated using data from three water utilities in Southern Ontario, Canada. The strategic targets and policy levers controlling these targets are established in the visions & values layer. The function layer uses the advanced system dynamics model to simulate and forecast each water utility's performance over their 100-year life cycle. The performance layer applies the entire set of Water related BPI's developed in Chapter 2 to benchmark three independent water utilities performance and to demonstrate their use. This study is limited to water distribution networks. Other components of an urban water infrastructure system are out of the scope of this part of this study.

3.3 Implementation Framework of Asset Management Strategy

This study develops an implementation framework for asset management strategy of water distribution networks comprised of three interconnected decision-making layers: (1) "visions & values", (2) "function", and (3) "performance", as shown in Figure 3.1.

3.3.1 Visions & Values Layer

The visions & values layer is set according to the established concepts of strategic targets, policy levers, sustainability and life cycle, as noted in Chapter 2 (Figure 2.1). Water utilities seeking to meet their visions & values should first set strategic targets, as noted in Table 3.1, and then adjust policy levers, as noted in Table 3.2, to sustainably maintain these targets over the life cycle of the infrastructure. A good asset management practice involves the utility's stakeholders in its decision-making layers. Four key stakeholders for a water utility are: (1) utility managers and employees, (2) customers (or community), (3) regulators, and (4) investors, as depicted in Figure 3.1. Utility managers and employees are involved in all three decision-making layers of asset management strategy. Customers and regulators are engaged in the visions and value layer of decision making where the utility's strategic targets and policy levers controlling these targets are established. This layer of decision making is intended to meet stakeholders' needs and comply with the mandated legislations. Investors are desired to have access and evaluate the utility's outcomes (i.e., the performance layer) to ensure an adequate return on their investments Figure 3.1).

Table 3.1: Strategic targets for asset management strategy of water distribution network

No.	Strategic Target	Description	Unit
1	$Min\ (infrastructure\ condition\ efficiency)$	Minimizes length of pipes over design life ($\mathbb{D}$), m (i.e., more than 75 years old) per capita, c.	(m/c)
2	$Min\ (water\ loss)$	With a value of zero water loss that indicates no water loss exist in the system	$(m^3)\ or\ (litre)$
3	$Min\ (liability)$	$(\frac{Liabilities\ (\$)}{Assets\ (\$)}) = 0$, with a value of zero indicating that the water utility has no liabilities (liability-asset ratio is zero).	$(-)$
4	$Min\ (water\ TotalEx\ efficiency)$	Minimizes water total expenditures divided by supplied water per length of network per capita.	$(\$/m^3/m/c)$

Table 3.2: Policy levers for asset management strategy of water distribution network

No.	Policy lever	Description	Unit
1	Preferred network rehabilitation rate	Percentage of total network length to be rehabilitated/replaced each year	$(\%/year)$
2	Desired cash reserve	Percentage of total network asset value	(%)
3	Maximum acceptable fraction of highly deteriorated pipes	Percentage of pipes older than 75 years	(%)
4	Desired elimination period for highly deteriorated pipes	Elimination period for pipes older than 75 years	$(year)$
5	Allowable fee-hike rate	The maximum allowable increase in user fee per year	$(\%/year)$
6	Debt capacity	Maximum allowable debt as percentage of total revenue	(%)

3.3.2 Function Layer

The function layer uses the advanced system dynamics model of this study, as presented in Section 3.4, to achieve the stated visions & values of the water utility. The system dynamics model explicitly models the feedback mechanisms among various components of the water distribution network. The outputs of the advanced system dynamics model are used to simulate and forecast the future performance of the system.

3.3.3 Performance Layer

Three groups of benchmarking performance indicators are developed in Chapter 2 for the water distribution network. These indicators are grouped into 1) infrastructure, 2) socio-political, and 3) financial. The BPI's are normalized to allow water utilities to benchmark themselves against each other locally, regionally and nationally, regardless of their size. Chapter 2 demonstrates the application of four BPI's to three water distribution networks to benchmark and compare system behaviour over a 100-year benchmarking period using the Rehan et al. (2013)'s system dynamics model. It is found that the analyzed BPI's can improve stakeholders understanding, support operational decisions and thus improve performance over time. The objective of this chapter is to implement all water BPI's in order to quantify the current and future performance of three water utilities in Southern Ontario, Canada.

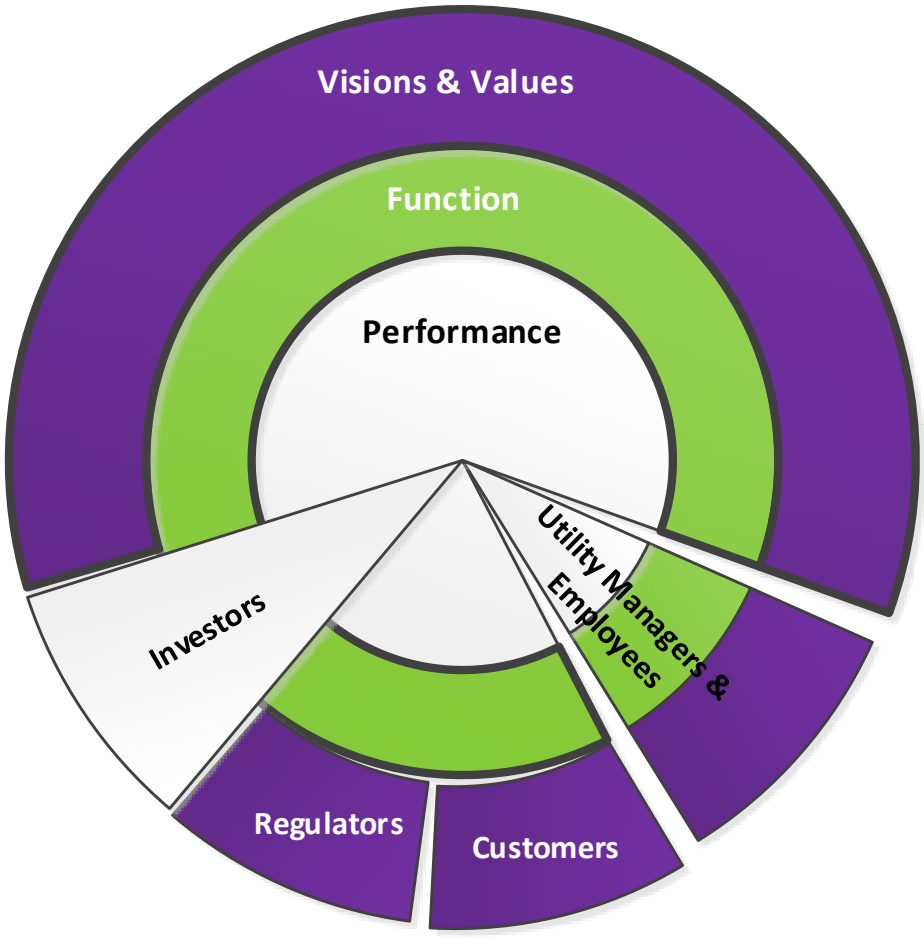


Figure 3.1**:** The utility key stakeholders' level of engagement in decision-making layers of asset management strategy: (1) visions & values, (2) function, and (3) performance

3.4 Water Distribution System Dynamics Model

A review of the Rehan et al. (2013; 2015) system dynamics models reveals some limitations associated with their model such as incomplete specification of fixed vs. variable revenue streams. In order to replicate the three water utilities analyzed in this study, the system dynamics model developed by Rehan et al. (2013) is further developed to overcome the limitations and hence quantify the function layer of the asset management strategy, as presented in Section 3.3. The SD model is developed using research version 9.1.4 of Stella® software (Richmond, Peterson, and Soderquist 2001) due to its useful features such as a library of built-in functions, capability of using graphical functions, and sensitivity analysis. The basic building blocks for SD models are: stocks, flows (inflow/outflow), converters, and connectors, as depicted in Figure 3.2.

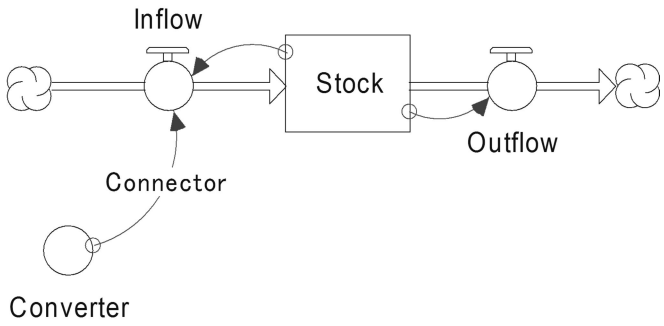


Figure 3.2: Building blocks of System Dynamics model

Stocks represent accumulations both physical and non-physical. For example, inventory of pipes and a customer's level of satisfaction. Stocks represent the 'traces' left by activities. Flows represent activities or actions. They transport quantities and can change instantaneously. The relationship between stocks and flows is represented as follow:

$$Stock(t) = \int [Inflow(t) - Outflow(t)]dt + Stock(t_0) \quad (3.1)$$

Connectors carry information to serve as inputs for decisions or actions. Converters are containers for performing algebra; they house graphical and built-in functions.

The advanced system dynamics model for water distribution network is comprised of three sectors: 1) infrastructure, 2) finance, and 3) socio-political. A description of these sectors is presented in the following sections.

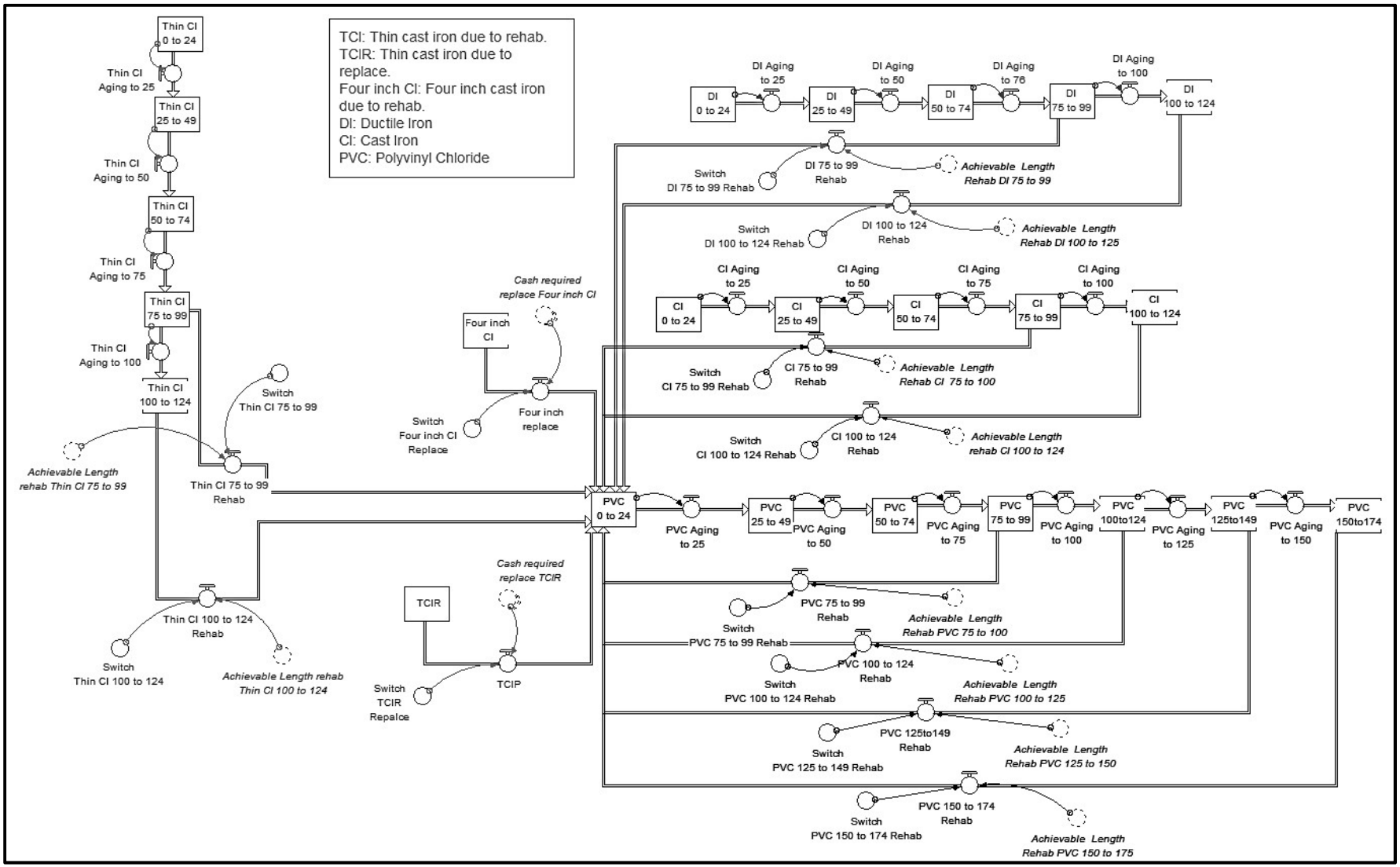
3.4.1 Infrastructure sector

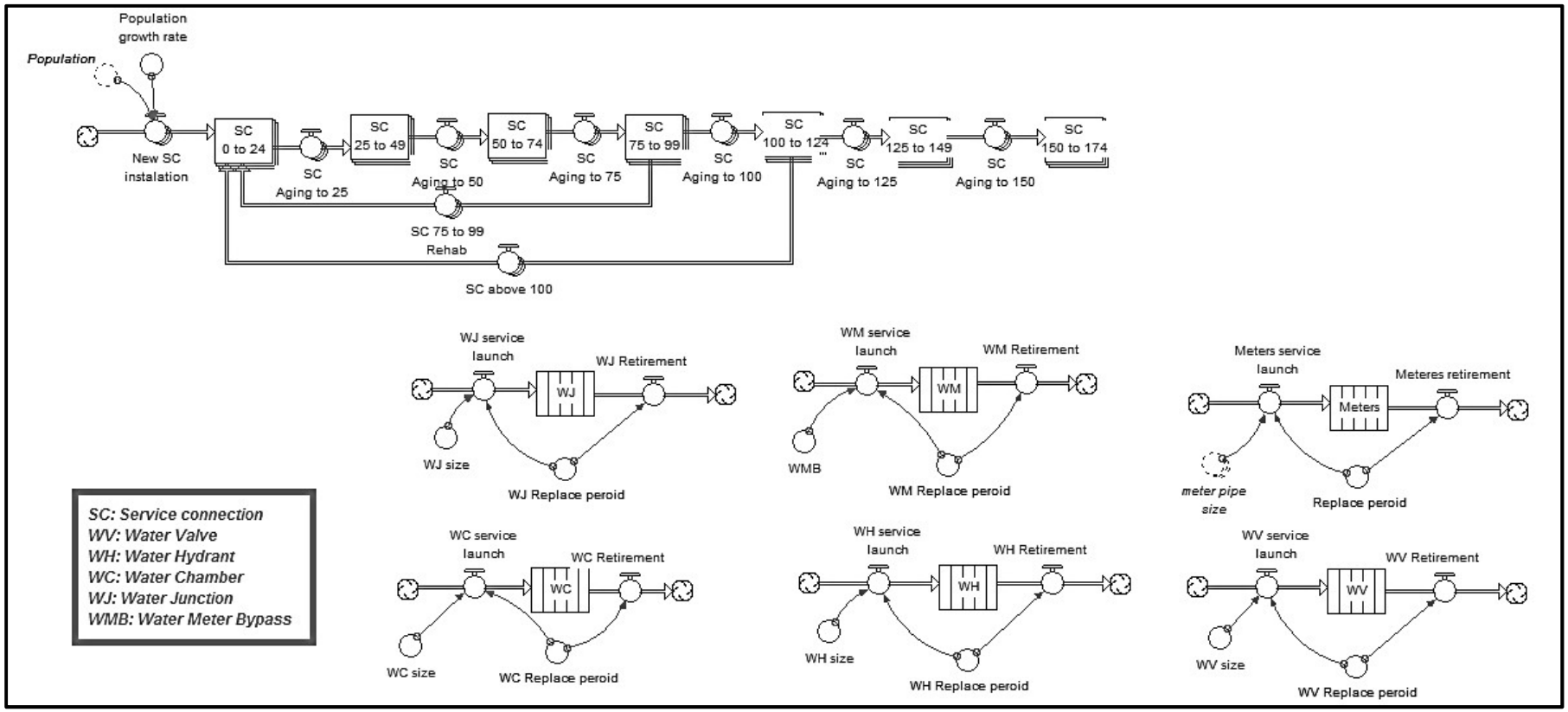
This sector represents the inventory of water distribution pipes. The American Water Works Association describes water distribution pipes as “pipelines that distribute water around a community” (AWWA 2010). The physical condition of water distribution networks is classified based on the age distribution of water mains within 25 year increments, as shown in

Figure 3.3a. For the purpose of applying their system dynamics model to three water utilities in Southern Ontario, this study creates an infrastructure sector model for each independent water utility to host their independent inventory of water main pipe segments. In addition to water mains, the other components of water distribution network are simulated in the infrastructure sector: 1) service connection, 2) valve, 3) hydrant, 4) chamber, 5) junction, 6) meter, and 7) meter bypass, as shown in Figure 3.3b.

The service connections are assumed to have the same behaviour as water mains with an aged-based (i.e., in a domain of 25 years) deterioration modeling paradigm. The other six components added to the infrastructure sector are simulated in an identical manner where each component is denoted with an initial inflow, stock, retirement outflow, and replacement period. For example, a water meter with a 15 years replacement period will be in service (i.e., WM stock) for 15 years having regular maintenance, and then will be retired (i.e., retirement outflow) and replaced with a new water meter.

a)


TCI: Thin cast iron due to rehab.
TCIR: Thin cast iron due to replace.
Four inch CI: Four inch cast iron due to rehab.
DI: Ductile Iron
CI: Cast Iron
PVC: Polyvinyl Chloride
Thin CI 0 to 24
Thin CI Aging to 25
Thin CI 25 to 49
Thin CI Aging to 50
Thin CI 50 to 74
Thin CI Aging to 75
Thin CI 75 to 99
Thin CI Aging to 100
Thin CI 100 to 124
Switch Thin CI 75 to 99
Achievable Length rehab Thin CI 75 to 99
Thin CI 75 to 99 Rehab
Thin CI 100 to 124 Rehab
Switch Thin CI 100 to 124
Achievable Length rehab Thin CI 100 to 124
Cash required replace Four inch CI
Four inch CI
Switch Four inch CI Replace
Four inch replace
TCIR
Cash required replace TCIR
Switch TCIR Repalce
TCIP
DI 0 to 24
DI Aging to 25
DI 25 to 49
DI Aging to 50
DI 50 to 74
DI Aging to 76
DI 75 to 99
DI Aging to 100
DI 100 to 124
Switch DI 75 to 99 Rehab
DI 75 to 99 Rehab
Achievable Length Rehab DI 75 to 99
Switch DI 100 to 124 Rehab
DI 100 to 124 Rehab
Achievable Length Rehab DI 100 to 125
CI 0 to 24
CI Aging to 25
CI 25 to 49
CI Aging to 50
CI 50 to 74
CI Aging to 75
CI 75 to 99
CI Aging to 100
CI 100 to 124
Switch CI 75 to 99 Rehab
CI 75 to 99 Rehab
Achievable Length Rehab CI 75 to 100
Switch CI 100 to 124 Rehab
CI 100 to 124 Rehab
Achievable Length rehab CI 100 to 124
PVC 0 to 24
PVC Aging to 25
PVC 25 to 49
PVC Aging to 50
PVC 50 to 74
PVC Aging to 75
PVC 75 to 99
PVC Aging to 100
PVC 100to124
PVC Aging to 125
PVC 125to149
PVC Aging to 150
PVC 150to174
PVC 75 to 99 Rehab
Switch PVC 75 to 99 Rehab
Achievable Length Rehab PVC 75 to 100
PVC 100 to 124 Rehab
Switch PVC 100 to 124 Rehab
Achievable Length Rehab PVC 100 to 125
PVC 125to149 Rehab
Switch PVC 125 to 149 Rehab
Achievable Length Rehab PVC 125 to 150
PVC 150 to 174 Rehab
Switch PVC 150 to 174 Rehab
Achievable Length Rehab PVC 150 to 175



b)

Figure 3.3: Infrastructure sector of the advanced system dynamic model in Stella®.

3.4.2 Finance sector

This sector describes the network's financial condition and includes: revenue, expenditures, fund balance, water fee, and etc., as shown in Figure 3.4. The Revenue is the water utility's income that is measured in terms of variable and fixed fees. The Fund Balance is the difference between the total income and total expenditures of the network in dollars value. The Water Fee is the amount of currency ($\$/m^3$) that a water utility charges its customers to pay the expenses associated with the water services.

The expenditures associated with water utility services to provide potable water to customers were restricted to only "variable costs" in the Rehan et al. (2013) system dynamics model. The "fixed costs" and "development charges" were not measured in their model. However, revenue data from each of the three water utilities included variable costs, fixed costs and development charges.

The customers of a water utility are required to pay for the costs associated with the supplied water based upon the volume of water consumption (Equation 3.2). They also need to pay a fixed cost for the services provided to them regardless of the amount of consumed water that is measured according to the size of service connections (pipe's diameter). The service connection delivers the treated water to each household (Equation 3.3). This study incorporates water service charges into the calculations of total revenue collected from the customers (Equation 3.4).

$$WD_{VC}(t) = Wf(t) \times \sum_{cc} MW(t) \qquad (3.2)$$

where, WD water distribution; VC variable cost ($); Wf water fee ($\$/m^3$); MW metered water (m^3); t time; cc classes of customers include residential, commercial and institutional.

$$WD_{FC}(t) = \sum_{d=15mm}^{d=Nmm} [WSC_d\,(t) \times NSC_d(t)] \qquad (3.3)$$

where, FC fixed cost ($); d diameter of service connection for $d = 15mm, 19mm, \dots, N$; N maximum diameter of service connection; WSC water service charges ($); NSC number of service connection.

Therefore, the new revenue (RV) in the advanced system dynamics model is measured as the sum of consumers' variable and fixed costs as:

$$WD_{RV}(t) = WD_{VC}(t) + WD_{FC}(t) = [Wf(t) \times \sum_{cc} MW(t)] + \sum_{d=15mm}^{d=Nmm} [WSC_d\,(t) \times NSC_d(t)] \quad (3.4)$$

Developers are also required to pay one-time development chargers (DC) for the expenditures associated with the extension of water distribution networks to the new developed areas. Development charges can be considered as a source of income for a wastewater utility, but revenue collected from customers in the form of variable and fixed costs is the major source of income. This study incorporates development charges into the finance sector as a source of total income for capital works. Therefore, the new fund balance (FB) is measured as given:

$$WD_{FB}(t) = WD_{Inc}(t) - WD_{Ex}(t)$$

$$WD_{FB}(t) = [WD_{RV}(t) + WD_{IE}(t) + WD_{DC}(t)] - [CapEx\ (t) + OpEx(t) + IntEx(t)]$$

$$WD_{FB}(t) = \left[\begin{array}{c} \left\{Wf(t) \times \sum_{cc} MW(t)\right\} \\ + \left\{\sum_{d=15mm}^{d=Nmm} WSC_d\ (t) \times NSC_d(t)\right\} \\ +\{WD_{IE}(t)\} + \{WD_{DC}(t)\} \end{array}\right] - [CapEx(t) + OpEx(t) + IntEx(t)]$$

$$Note: for\ WD_{IE}(t), \qquad If\ WD_{FB}(t) > 0\ Then\ WD_{IE}(t) = WD_{FB}(t) \times Sr(t)$$

$$Else\ WD_{IE}(t) = 0 \qquad (3.5)$$

where, Inc income (\$); IE interest earnings (\$) is a source of income accrued on water utility's positive fund balance (cash reserves); Sr saving rate ($\%/year$); $CapEx$ capital expenditures (\$); $OpEx$ *operational* expenditures (\$); $IntEx$ interest expenditures (\$).

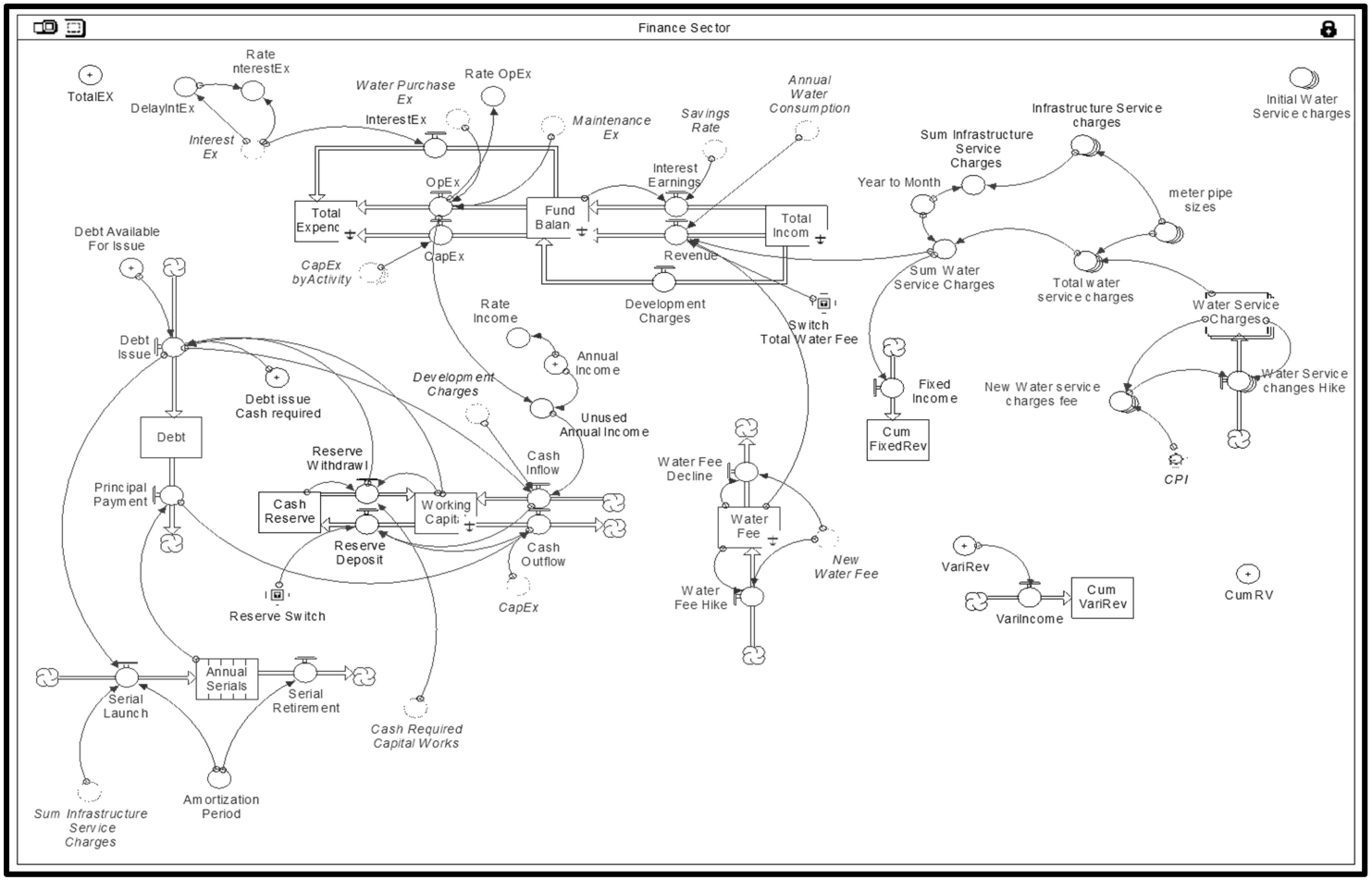


Figure 3.4: Finance sector of the advanced system dynamic model in Stella®

3.4.3 Socio-political sector

This sector presents the consumption behaviour of customers in response to water fee oscillations and level of service delivered to them, as shown in Figure 3.5. It requires information such as water demand, price elasticity of water demand, minimum water demand, demand adjustment period and population. Price elasticity of water demand was modeled as a constant parameter in the system dynamics model developed by Rehan et al. (2013) for water distribution networks. In this study, price elasticity of water demand is expanded to contain different classes of customers: 1) residential, 2) commercial, and 3) institutional, as depicted in Figure 3.5. Subsequently, water demand and annual water consumptions are measured and tracked based on different classes of customers.

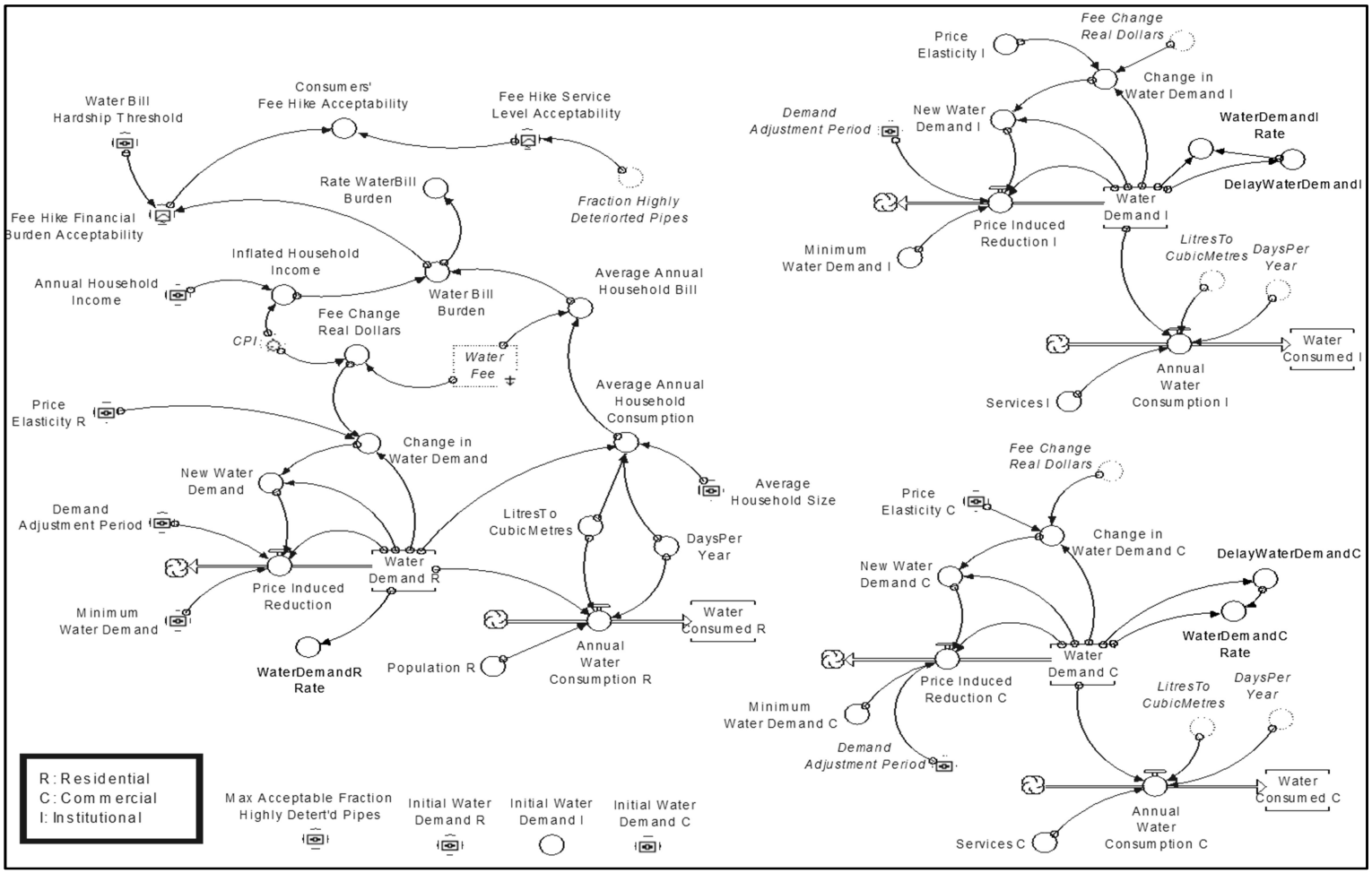


Figure 3.5: Socio-political sector of the advanced system dynamic model in Stella®.

3.5 Asset Management Strategy Implementation

The three decision-making layers developed for asset management strategy of the water distribution network is validated using data from three water utilities in Southern Ontario, Canada, arbitrarily called X, Y and Z.

3.5.1 Data and parameters for Utilities X, Y and Z

Strategic targets and policy levers controlling the strategic targets, as noted in Table 3.1 and Table 3.2, respectively, are made as identical as possible between each utility under the assumption they will have similar preferences (due in part to their geographic proximity) for strategic targets, policy levers, sustainability, and life cycle. A capital reserving financing strategy is implemented for all three utilities considered over a 100-year benchmarking period, and is used to establish a capital reserve of 4% of the network replacement value.

The preferred network rehabilitation rate (policy lever 1) is set at 1.3% of the network per year to reflect desired utilities practice and target rate recommended by the Canadian Infrastructure Report Card (2016). Policy lever 2 allows the water utilities to build-up cash reserves of up to 4% of the replacement value of their network. Policy lever 3 is set at 5%, indicating that the utility will allow up to 5% of its network pipes to be in the worst structural condition. If the 5% threshold is exceeded, a network rehabilitation rate higher than the preferred rate of 1.3% is required to eliminate deteriorated pipes in the network within the elimination period of five years (policy lever 4). Policy lever 5 controls the peak fee hike rate and allows the water utilities to generate revenue to pay for capital and operational expenses, as well enabling them to build up their target cash reserve. Through trial and error, the optimal allowable water fee-hike rates (policy lever 5), for financially sustainable management of the water distribution network, are found to be 8.5% per annum for utility X, 9% per annum for utility Y, and 10.5% per annum for utility Z.

To simulate and run the advanced system dynamics model for the three water utilities, significant data have been collected on component/parameters of infrastructure, finance, and socio-political sectors. Demographic information of water utilities X, Y and Z include population and water main length are summarized in Table 3.3. Their networks are comprised of pipes made of polyvinyl chloride (PVC), cast

iron (CI), ductile iron (DI), and asbestos cement (AC). Initially, 5.5, 8 and 8.5 percent of their respective network lengths are in the worst structural condition (i.e., more than 75 years old).

Table 3.3**:** Demographic information of water utilities

Water Utility	**X**	**Y**	**Z**
Population $[c]$	120,000	130,000	83,000
Water main length $[m]$	361,000	501,000	450,000
Infrastructure Efficiency $[m/c]$	3.0	3.85	5.42
Infrastructure Density $[m/m^2]$	5.4×10^{-3}	4.4×10^{-3}	2.1×10^{-3}

The current water fees utilities charge their customers are $\$1.55, \$1.68\ and\ \$0.92/m^3$ for utilities X, Y and Z, respectively. The current cost of water treatment is reported $\$0.83/m^3$ for utilities X and Y and $\$0.54/m^3$ for utility Z. Typical average daily water consumption in the local region is 280 liters per capita per day ($lpcd$) for utilities X and Z and 322 $lpcd$ for utility Y. The minimum water demand for the three utilities is assumed to be 150 $lpcd$. Price elasticity of water demand for the residential sector is assumed to be equal to -0.35 which is the average of the range reported by Boland et al. (1984) and Olmstead et al. (2007), used by Rehan et al. (2011; 2014b; 2015), and used in the research described in Chapter 2.

The current unit cost for rehabilitating pipes 75 to 100 years old is reported $600 per meter, and for pipes more than 100 years old, it is set at $700 per meter for the three utilities. The unit operation and maintenance costs and leakage rate are calculated in a manner identical to Section 2.5.1. The 6.4% per annum inflation rate reported by Younis et al. (2016) for water main construction projects is used in this study to inflate the unit cost of pipe renewal ($\$/m$), the unit cost of pipe maintenance ($\$/m/year$), and the unit price of treated water ($\$/m^3$). The household income is inflated over the benchmarking period with the rate of 2.4% per annum reported by the customer price index (CPI) of Canada (Statistics Canada 2014).

3.6 Results

This section presents the benchmarking results of the three interconnected decision-making layers for asset management strategy of three water utilities over a100-year benchmarking period, as illustrated in Figures 3.6-3.8.

3.6.1 Infrastructure performance indicators

This category measures the infrastructure performance of the water distribution network. The BPI of infrastructure efficiency and density for each utility are provided in Table 3.3. For this study, the water network length, population and area serviced by the utility are assumed to be constant over the benchmarking period. Therefore, the infrastructure efficiency and density with values noted in Table 3.3 are constant over the benchmarking period for the three utilities. The other three BPI's are presented for the three utilities to demonstrate a) infrastructure condition efficiency (m/c), b) rehabilitation efficiency ($\%/yr$), and c) water loss efficiency ($l/m/c/yr$). The performance indicators of this category are illustrated with water utilities X, Y and Z in Figure 3.6.

The results of this category show that the three utilities achieve the stated strategic target of Min (infrastructure condition efficiency), with the controlling policy lever 1 (i.e., preferred rehab rate of 1.3% of the network per year), policy lever 3 (i.e., no more than 5% of pipes in the worst structural condition), and policy lever 4 (i.e., eliminating period of 5 years for pipes in the worst structural condition). In addition, the strategic target of Min ($water\ loss$) is achieved for the three utilities, as illustrated in Figure 3.6c. Therefore, the three water utilities sustainably maintain these targets over the life cycle of the infrastructure.

Figure 3.6a shows the BPI of infrastructure condition efficiency that measures an infrastructure system's efficiency in terms of fraction of highly deteriorated pipes (+75 years) per capita (m/c). In general, the benchmarking results show the same trend for the three utilities. For water utility X, the infrastructure condition efficiency starts with a value of $0.17\ m/c$, decreases to $0.02\ m/c$ at 6 years, then decreases linearly to the age of 60 years, followed by linear increases to the end of the benchmarking period to reach the value of $0.04\ m/c$ (Figure 3.6a). For water utility Y, the infrastructure condition efficiency starts at a value of $0.34\ m/c$, declines to $0.02\ m/c$ at 5 years, then increases linearly to the age of 42 years, followed by a decline to 58 years, and a continuous climb linearly to the end of the benchmarking period to reach a final value of $0.63\ m/c$ (Figure 3.6a). For water utility Z, the f infrastructure condition efficiency starts with a value of $0.47\ m/c$, decreases to $0.06\ m/c$ at 10 years, continues to decline linearly to the age of 42 years, and then is followed by a continues increase linearly to the end of the benchmarking period to reach a final value of $0.1\ m/c$ (Figure 3.6a).

Water utility Z has the highest fraction of highly deteriorated pipes (m/c) beyond 10 years. This is due to the allowable fee-hike rate for utility Z being set too low such that insufficient revenues exist to replace

the fraction of highly deteriorated pipes at given times. However, all utilities eventually comply with the policy lever 4, such that no more than five percent of the network is in a deteriorated condition. This suggests that rehabilitating 1.3 percent of the network length per year (i.e., policy lever 1) appears to be achieved over the life-cycle of the infrastructure for all three water utilities.

Figure 3.6b shows the BPI of rehabilitation efficiency ($\%/yr$). Water utility Z starts this benchmarking exercise with the oldest inventory of pipes and the highest fraction of deteriorated pipes (see Figure 3.6a). Consequently, it has the highest value of rehabilitation efficiency for the first 45 years of the benchmarking period, as shown in Figure 3.6b. Rehabilitation efficiency BPI measures the percentage of actual rehabilitation/replacement to the stated rehabilitation/replacement target. As this percentage approaches unity (i.e., 100 percent), the policy lever of rehabilitating/replacing 1.3 percent of the network length per year appears to be achieved over the life-cycle of the infrastructure for all three water utilities.

For water utility X, the rehabilitation efficiency starts with a value of 100 percent, remains constant for 6 years, followed by a sudden decline to reach the minimum value of 52 percent at 10 years, and then is followed by a continuous increase to the age of 45 years to reach the value of 100 percent and remains constant to the end of benchmarking period (Figure 3.6b). For water utility Y, the rehabilitation efficiency starts with a value of 100 percent, climbs to 127 percent at 5 years, followed by a sudden decline to 42 percent at 7 years, and a continuous climb to 100 percent at 45 years and remains constant to the end of the benchmarking period (Figure 3.6b). For water utility Z the rehabilitation efficiency starts with a value of 100 percent, followed by a continuous increase in the first 2.5 years to reach its maximum value of 132 percent at 2.5 years and remains constant to the age of 10 years, followed by a sudden decline to 85 percent at 15 years, and then followed by a continues climb to 100 percent at 45 years and remains constant to the end of the benchmarking period (Figure 3.6b).

Figure 3.6c depicts water loss efficiency BPI by measuring water loss per meter length of network per capita over the benchmarking period ($l/m\ /c/yr$). The water loss efficiency BPI starts with values of $0.036, 0.015\ and\ 0.06\ l/m\ /c/yr$ for water utilities X, Y and Z, respectively. This performance indicator declines for the three utilities implying that they all achieve the stated target of minimizing water loss over the benchmarking period. Utility Z has the highest water loss given as water loss divided by network length, population, and the benchmarking period ($l/m\ /c/yr$). This is a function of utility Z

initially having the oldest inventory of pipes. In contrast, utility X has the lowest water losses given its youngest inventory of pipes (Figure 3.6a).

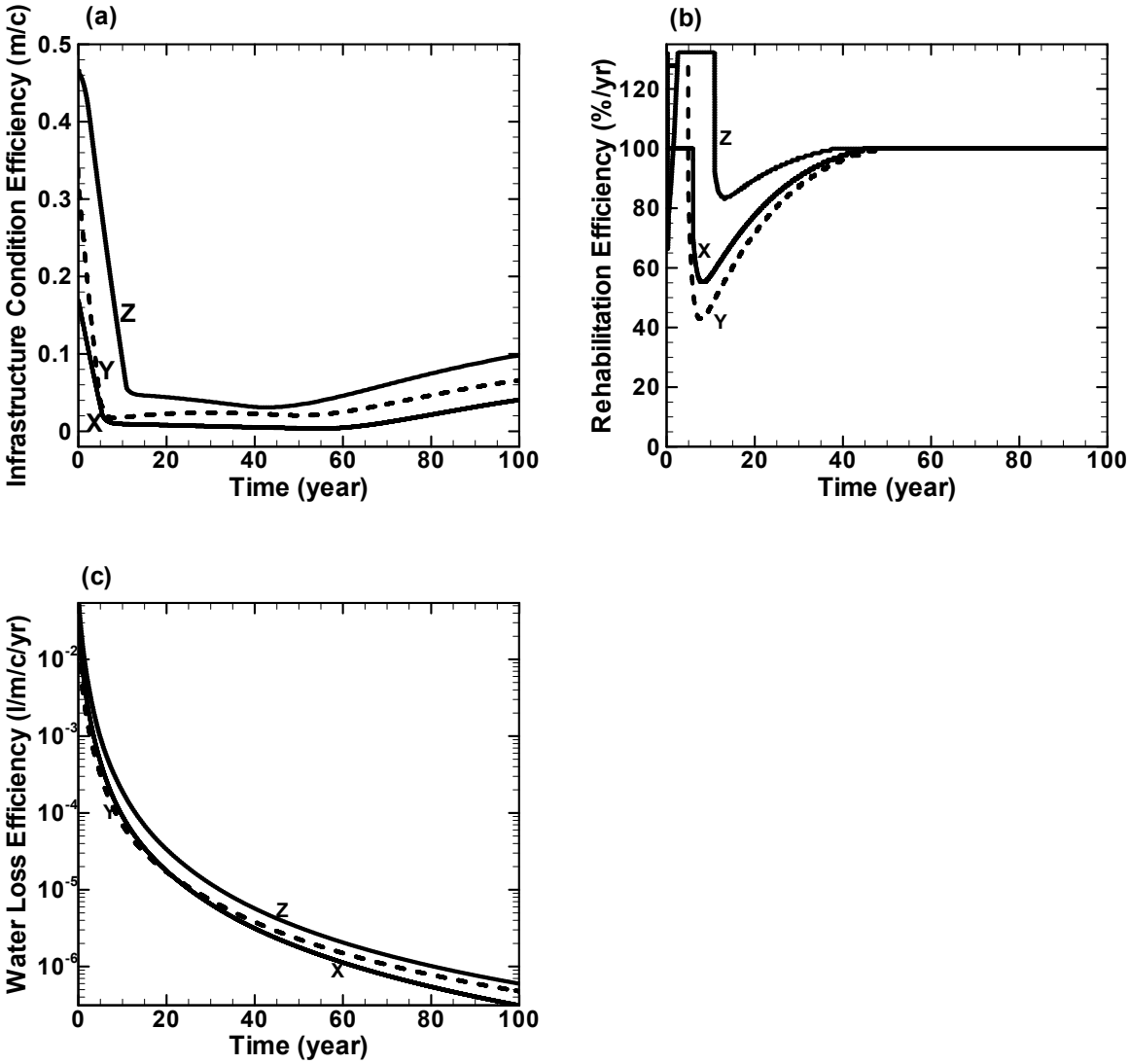


Figure 3.6: Water infrastructure performance indicators over a 100-year benchmarking period for utilities X, Y and Z.

3.6.2 Socio-political performance indicators

This category measures the socio-political performance of three water utilities in terms of a) fee hike ratio (%), b) metered water efficiency (m^3/m^3), and c) metered water loss ratio (m^3/m^3). The results of this

category show that the three utilities can achieve the stated strategic targets of $Min\ (Water\ Losses)$, as shown in Figures 3.7b and 3.7c.

Figure 3.7a shows fee hike ratio BPI for the three water utilities. This performance indicator is measured as percentage of current fee hike to allowable fee hike over the benchmarking period, as described in Chapter 2, Section 2.4.2. The value of one indicates that the current fee hike rate equals to the allowable fee hike ratio. The fee hike ratio shows some oscillations in the first 30 years for all three water utilities (Figure 3.7a). The results show that this ratio hits the maximum value of unity at 30 years and remains constant between 4-5 years, followed by a sudden decline and continues to decrease linearly to the end of the benchmarking period to reach final values of 0.8, 0.75 and 0.65 percent for utilities X, Y and Z, respectively (Figure 3.7a).

The BPI of metered water efficiency (m^3/m^3) as ratio of supplied to metered water is illustrated in the Figure 3.7b. The difference between supplied and metered water is water loss. The optimum value for this performance indicator is obtained with the value of unity indicating no water loss exists in the water distribution network. The BPI of metered water efficiency starts with initial values of 1.12, 1.06 and1.25 for water utilities X, Y and Z, respectively, followed by a decline to their minimum values of 1.02, 1.03 and 1.04, respectively at the end of the benchmarking period. Figure 3.7b indicates that water utility Z has the highest metered water efficiency compared to the other two utilities due to its highest infrastructure condition efficiency, as shown in Figure 3.6a.

Figure 3.7c shows metered water loss ratio BPI (m^3/m^3) as ratio of water loss to metered water. It shows the initial values of 0.115, 0.07 and 0.24 for water utilities X, Y and Z, respectively, followed by a decline to their minimum values of 0.02, 0.03 and 0.045, respectively at the end of the benchmarking period. The value of zero represents the optimum value for the BPI of metered water loss ratio which means no water loss exist in the system, or supplied water is equal to water metered. Similar to the BPI of metered water efficiency, as depicted in Figure 3.7b, water utility Z has the highest water loss over the benchmarking period (Figure 3.7c).

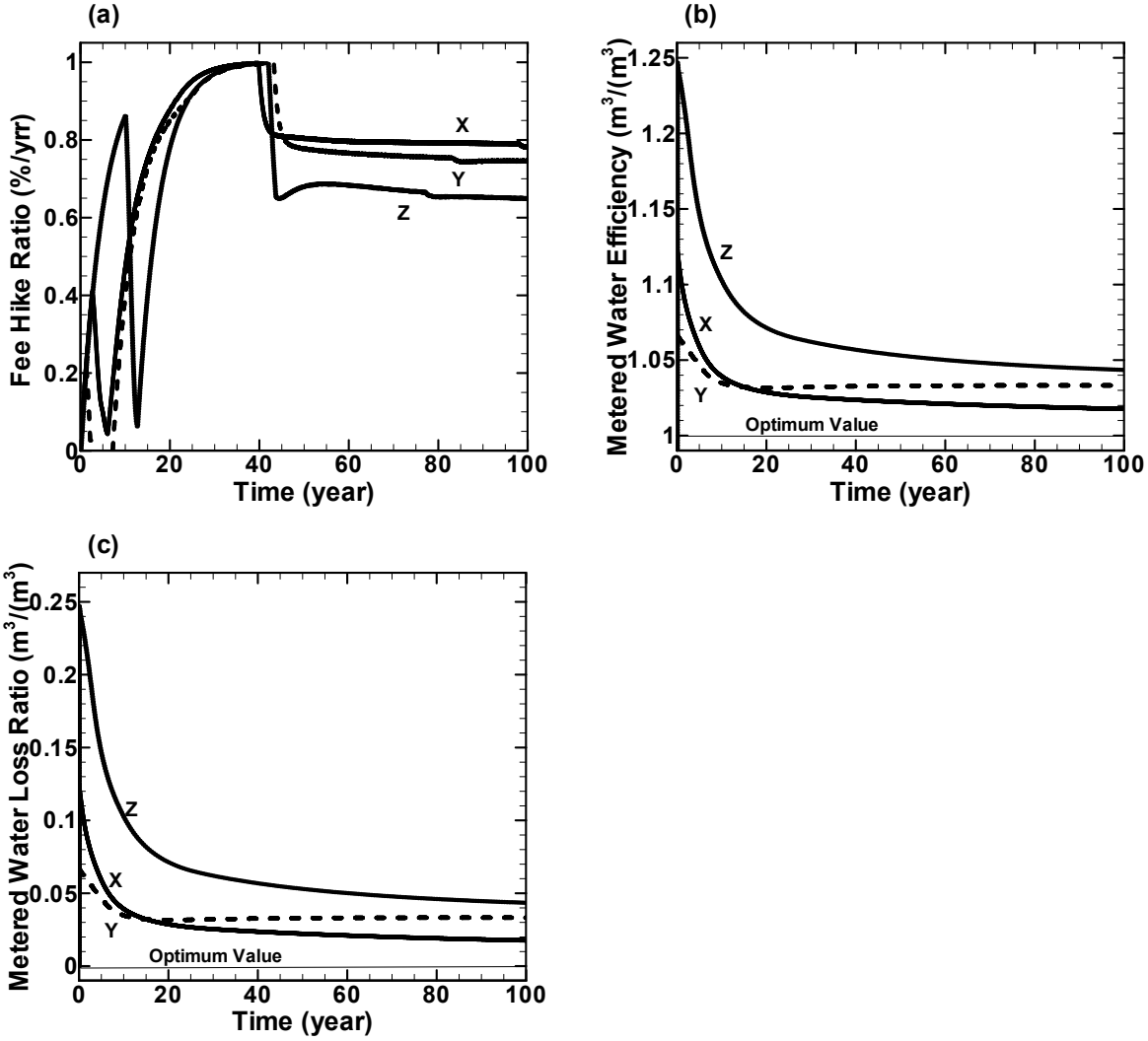


Figure 3.7: Water socio-political indicators over a 100-year benchmarking period for utilities X, Y and Z.

3.6.3 Financial performance indicators

Financial performance of the water distribution network for each utility is benchmarked using the eight water distribution network BPI's established in Chapter 2. The water utility is not required to issue debt under capital reserving scenario, thus the BPI of water debt efficiency is $\$0/m^3/m/c$ over the benchmarking period for all three water utilities. The benchmarking results for the remaining seven financial performance indicators are illustrated in Figure 3.8. The results indicate that the three utilities

meet the strategic targets of 1) $Min\ (water\ TotalEx\ efficiency)$ by minimizing non-RevenueEx efficiency (Figure 3.8b), 2) $Min\ (water\ loss)$; and 3) $Min\ (liability)$.

Figure 3.8a shows water TotalEx efficiency BPI for the three water utilities. In general, the results show a linear trend with some curvature. The water TotalEx efficiency BPI starts with a value of $\$0.22/m^3/m/c$ for water utilities X and Z, and $\$0.16/m^3/m/c$ for water utility Y, in the first 20 years followed by some oscillations, and continues to increase to the end of the benchmarking period to reach the value of $\$0.5, \$0.41\ and\ \$0.52/m^3/m/c$ for utilities X, Y and Z, respectively (Figure 3.8a). Residents of utility Z spend more dollars per cubic meter of supplied water per meter of network length per capita compared to the other water utilities. In contrast, residents of utility Y spend the least dollars per cubic meter of supplied water per meter of network length per capita with the presumption that their water distribution system is the most efficient. This expense is essentially the ratio of: total water distribution expenditures divided by supplied water $[\$/m^3]$; and, infrastructure efficiency (m/c). In summary, the three utilities ultimately achieve similar behaviour over the entire benchmarking period with the spread in their water TotalEx efficiency never separating by more than approximately \$0.11 $m^3/m/c$. The spread persists due to the assumption of constant population and network length combined with the peak fee hikes rate that permits each water utility to have sufficient revenue to meet expenses over the benchmarking period.

The non-RevenueEx efficiency BPI is illustrated in Figure 3.8b. This BPI is measured in terms of water loss expenditures per cubic meter of supplied water per meter of network length per capita. The non-RevenueEx efficiency starts with the initial values of $\$0.03, \$0.01\ and\ \$0.02/m^3/m/c$ for water utilities X, Y and Z, respectively. The results show the same declining trend for utilities X and Z to the end of the benchmarking period to reach their minimum values of $\$0.008\ and\ \$0.007/m^3/m/c$. For water utility Y, it starts with a value $\$0.05/m^3$, declines for 10 years, and then is followed by a continuous increase to the end of benchmarking period to reach the value $\$0.01\ /m^3/m/c$ (Figure 3.8b).

Figure 3.8c shows water OpEx efficiency BPI for the three water utilities. The results show the same trend for all three water utilities. The water OpEx efficiency BPI starts with initial values of $\$0.11, \$0.07\ and\ \$0.14/m^3/m/c$ for water utilities X, Y and Z, respectively, in the first 20 years followed by some oscillations, and continues to increase to the end of the benchmarking period to reach the value of $\$0.27, \$0.20\ and\ \$0.26/m^3/m/c$ for utilities X, Y and Z, respectively (Figure 3.8c).

All utilities achieve similar behaviour over the entire benchmarking period with the spread in their water OpEx efficiency never separating by more than approximately \$0.07 $m^3/m/c$. In summary, the three utilities comply with the policy lever that no more than 5 percent of the network is in a deteriorated condition.

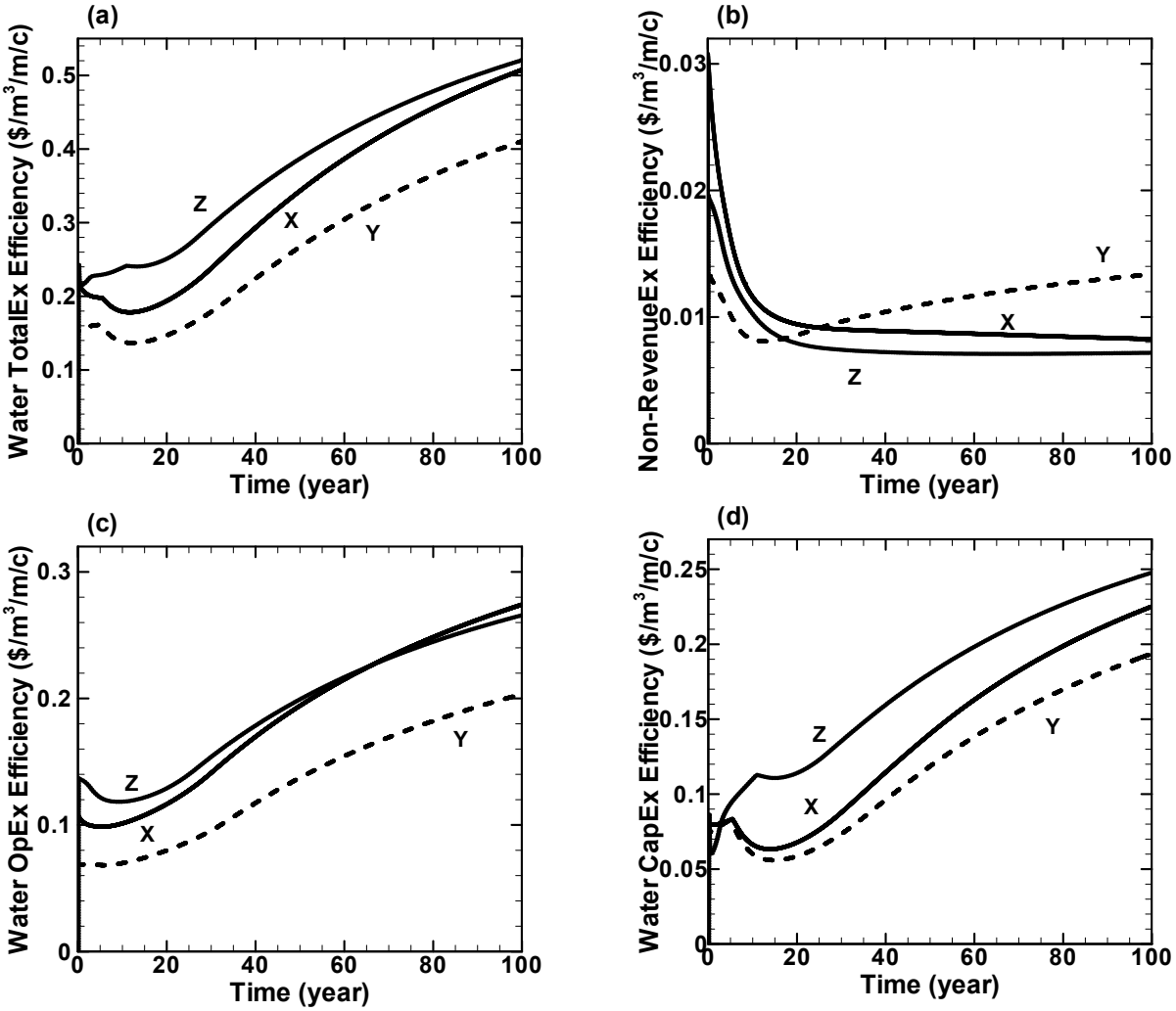
Figure 3.8d shows water CapEx efficiency BPI that is measured in terms of capital expenditures over supplied water per meter of network length per capita. The water CapEx efficiency BPI starts with the initial values of $\$0.08, \$0.06 \; and \; \$0.07/m^3/m/c$ for water utilities X, Y and Z, respectively. In general, the results show some oscillations in the first 20 years, followed by a linear increase to the end of the benchmarking period to reach the value of $\$0.22 \; \$0.18 \; and \; \$0.25/m^3/m/c$ for utilities X, Y and Z, respectively (Figure 3.8d). All three utilities show the same behaviour over the 100 year with the spread in their water CapEx efficiency never separating by no more than \$0.07 $m^3/m/c$, respectively. In summary, the three utilities comply with the policy lever that no more than 5 percent of the network is in a deteriorated condition.

Figure 3.8e shows OpEx ratio BPI for the three water utilities. The OpEx ratio BPI determines whether a water utility achieves its operational program targets by measuring the ratio of operational expenditures over the revenue (see Chapter 2, Section 2.4.3). Generally, the results show the same declining trend beyond 20 years. The OpEx ratio BPI starts with a value of 0.83, 0.69 and 0.80 for water utilities X, Y and Z, respectively, and follows with some oscillations in the first 20 years, followed by a decline to the end of the benchmarking period to reach the values of 0.76, 0.72 and 0.61 percent for water utilities X, Y and Z, respectively.

The CapEx ratio BPI for the three water utilities is illustrated in Figure 3.8f. The CapEx ratio BPI determines whether a water utility achieves its capital works targets by measuring the ratio of capital expenditures over the revenue (see Chapter 2, Section 2.4.3). In general, the results show a linear trend with some curvature. The CapEx ratio BPI starts with a value of 0.17, 0.12 and 0.20 for water utilities X, Y and Z, respectively. In the first 15 years, it is followed by some oscillations, and continues to increase to the end of the benchmarking period to reach the value of 0.21, 0.23 and 0.33 percent for utilities X, Y and Z, respectively (Figure 3.8e). Water utility Z has the highest value of CapEx ratio BPI over the benchmarking period due to its oldest inventory of pipes and the highest infrastructure condition efficiency value (Figure 3.6a). Therefore, it requires spending more funds on capital works to comply with the policy lever that no more than 5 percent of the network in a deteriorated condition. Water utility

X has the lowest value of CapEx ratio due to its lowest value of infrastructure condition efficiency (Figure 3.6a) beyond five years in the benchmarking period, as depicted in Figure 3.6c.

The BPI of liability-asset (L/A) ratio, as shown in Figure 3.8g is measured as a percentage of total liabilities relative to total assets for a water utility (see Chapter 2, Table 2.5). The benchmarking result indicates that applying capital reserving management strategy enables water utilities to reserve cash and have enough funds to accelerate capital works projects with no or minimal liability over the benchmarking period. The L/A BPI starts with the initial value of zero percent for all three water utilities indicating no liability at time zero, followed by an increase to reach its maximum value of 1.1%, 1.8% and 2.8% for utilities X, Y and Z, respectively, and declines to the end of the benchmarking period to reach the value of 0%, 1.1% and 1.5% for utilities X, Y and Z, respectively at the end of benchmarking period.


(a)
Water TotalEx Efficiency ($/m3/m/c)
0
0.1
0.2
0.3
0.4
0.5
0
20
40
60
80
100
Time (year)
Z
X
Y
(b)
Non-RevenueEx Efficiency ($/m3/m/c)
0
0.01
0.02
0.03
Time (year)
Y
X
Z
(c)
Water OpEx Efficiency ($/m3/m/c)
0
0.1
0.2
0.3
Time (year)
Z
X
Y
(d)
Water CapEx Efficiency ($/m3/m/c)
0
0.05
0.1
0.15
0.2
0.25
Time (year)
Z
X
Y

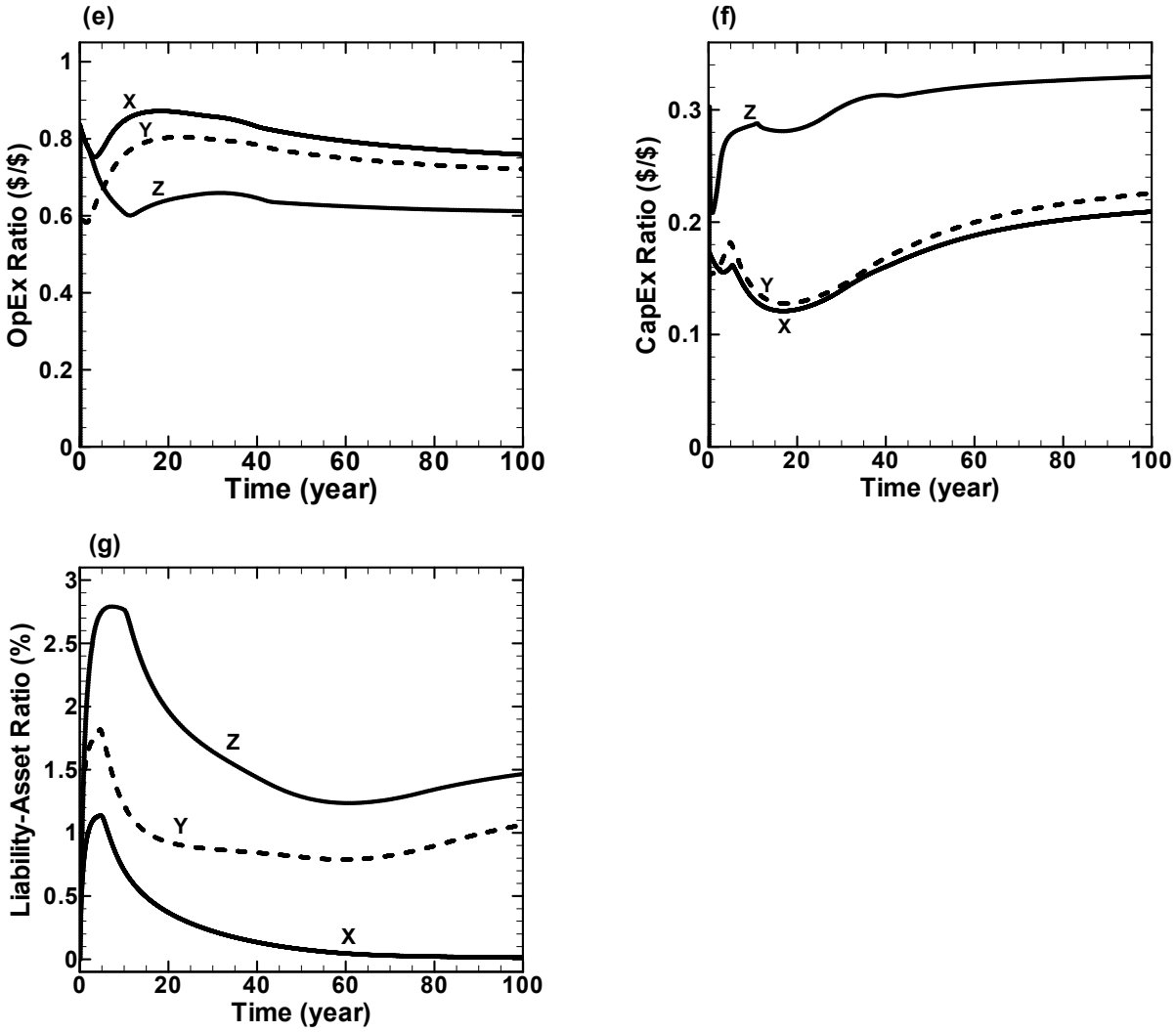


Figure 3.8: Water financial performance indicators over a 100-year benchmarking period for utilities X, Y and Z.

3.7 Discussion

This study demonstrates a unified implementation framework for asset management strategy of water utilities to meet sustainable infrastructure, socio-political, and financial targets over the life cycle of the infrastructure. The advanced system dynamics model creates three distinctive models for each independent utility to host their infrastructure, financial and socio-political characteristics. The forecasting feature of the advanced system dynamics model (i.e., function layer) enables water utilities to plan future actions required to meet stakeholders' objectives. In addition, the water utility can benchmark

and compare success at achieving their strategic targets established in the visions and values layer across utilities regardless of the utility size. The application of the entire BPI's demonstrates the complexity of water distribution system and allows a better understanding of the total system responses.

Kleiner (1998) indicated that water loss from a pipe is a function of its structural condition. Utility Z starts this benchmarking exercise with the oldest inventory of pipes and the highest fraction of deteriorated pipes whereas utility X starts with the youngest inventory of pipes and the lowest fraction of deteriorated pipes, as shown in Figure 3.6a. Therefore, more capital works are required for utility Z compare to other two utilities, as shown in Figure 3.8d to reduce water loss and the associated expenditures, as shown in Figures 3.6c and 3.8b, respectively over the benchmarking period. Utilities X and Y show the same behavior as utility Z on water loss efficiency, as shown in Figure 3.6c.

The results show that the three utilities achieve the strategic targets of 1) $Min\ (infrastructure\ condition\ efficiency)$; 2) $Min\ (water\ loss)$, the BPI's of water loss efficiency, metered water efficiency, and metered water loss ratio; 3) $Min\ (nonRevenueEx\ efficiency)$; and 4) $Min\ (liability)$, the BPI of liability-asset ratio. Therefore, all three water utilities sustainably maintain these targets using the controlling policy levers, as noted in Section 3.5.1.2, over the benchmarking period.

3.7.1 Effect of desired cash reserve on infrastructure and financial BPI's

The three water utilities performance over the 100-year benchmarking period discussed in the previous section involved only a 4% desired cash reserve. Moreover, each water utility had a common set of allowable fee-hike with a 1.3% preferred network rehabilitation rate for the three utilities. To gain further insights regarding the impact of desired cash reserve on infrastructure and financial performance indicators, it is instructive to explore network management strategies over a broader range of two policy levers: 1) allowable fee-hike rate, and 2) network rehabilitation rate, as noted in Section 3.5.1.2. This is accomplished by creating three scenario sets corresponding to desired cash reserve values of 1, 2.5, and 4%. Within each scenario set, the allowable fee-hike rate is varied over a range of 0% to 12% per annum, and preferred network rehabilitation rate is varied over a range of 0% to 3% per annum. It is assumed that allowable fee-hike rate in excess of 12% per annum is not a politically feasible strategy for the water utility to sustain over the long run. Similarly, a capital-works plan rehabilitating in excess of 3% of the network per year is assumed not feasible due to availability of physical and financial resources. Policy levers for the three scenario sets are provided in Table 3.4. The effect of desired cash reserve is presented

on two selected BPI's that represent infrastructure and financial performance of water utilities. The BPI of infrastructure condition efficiency (m/c) is selected for infrastructure performance, and the BPI of water TotalEx efficiency ($\$/m^3/m/c$) is selected for financial performance of the utility over the benchmarking period.

Table 3.4: Policy levers for three scenario sets.

Policy Lever	Scenario Set 1	Scenario Set 2	Scenario Set 3
Desired cash reserve (as percent of total network length)	1	2.5	4
Maximum acceptable fraction of pipes over 75 years (%)	5	5	5
Desired elimination period of pipes over 75 years (years)	5	5	5
Allowable fee-hike rate (percent per year)	0 to 12	0 to 12	0 to 12
Preferred rehabilitation rate (% of network per year)	0 to 3	0 to 3	0 to 3

Figures 3.9a, 3.9b and 3.9c present the contours of maximum BPI of infrastructure condition efficiency that is length of pipes over 75 years per capita (m/c) for scenarios 1, 2 and 3 with 1, 2.5 and 4% desired cash reserve, respectively. These contours are the mean BPI values arising from the simulations (3,969 runs) for the three utilities. For comparative purposes, water utilities X, Y and Z with the unique set of allowable fee hike and a 1.3% preferred network rehabilitation, as discussed in the previous section are illustrated as white dots on Figures 3.9a, 3.9b and 3.9c, respectively. Figures 3.9d, 3.9e and 3.9f show contours of the water TotalEx efficiency, as measured in terms of total water distribution expenditures divided by supplied water per length of water network per capita ($\$/m^3/m/c$), at 100 years for scenarios with 1, 2.5 and 4% desired cash reserve, respectively. These contours are also the mean BPI values arising from the simulations (3,969 runs) for the three utilities. Once again, for comparative purposes, water utilities X, Y and Z are depicted as white dots on Figures 3.9d, 3.9e and 3.9f, respectively.

Figures 3.9a to 3.9c indicate that the value of infrastructure condition efficiency (m/c) decreases as the allowable fee-hike rate increases over the benchmarking period. The least (m/c) region is shown with blue contour for desired cash reserve of 1%, 2.5% and 4%. From a socio-political and administrative perspective, it is desirable for the water utility to operate on boundary of the blue contour. The results of Figures 3.9a and 3.9b show that the desired cash reserve of 1% and 2.5% do not provide sufficient funds for the original scenarios of water utilities X and Y (Section 3.5), as depicted with white dots on

Figures3.9a and 3.9b, respectively to be in or near the blue region. The desired cash reserve of 4% provides sufficient funds for utilities X and Y to move into the blue region, as illustrated in Figure 3.9c. For the original scenario of water utility Z (Section 3.5), as shown with dots on Figures 3.9a to 3.9c, the value of infrastructure condition efficiency BPI shows the same behavior with desired cash reserve from 1% to 4% and remains in the blue region.

Figures 3.9d to 3.9f indicate that the water TotalEx efficiency, as a financial BPI, has a similar shape to the infrastructure condition efficiency and decreases as the allowable fee-hike rate increases over the benchmarking period. The least ($\$/m^3/m/c$) region is shown with blue contour for desired cash reserve of 1%, 2.5% and 4%. The results of Figures 3.9d and 3.9e show that the desired cash reserve of 1% and 2.5% do not provide enough funds for the original scenarios of water utilities X and Y (Section 3.5), as depicted with white dots on Figures 3.9d and 3.9e, respectively to be in or near the blue region. The desired cash reserve of 4% provides utilities X and Y with sufficient funds to move into the blue region, as illustrated in Figure 3.9f. For the original scenario of water utility Z (Section 3.5), as shown with dots on Figures 3.9d to 3.9f, the value of water TotalEx efficiency shows similar behaviour with desired cash reserve from 1% to 4% and remains in the blue region.

Note that these contours are stable in the sense that the three utilities are used to create them. Hence, more data from additional utilities could be used to depict a global optimal solution for all utilities to conform to.

The most important observation is that contours representing the “optimal” combination of allowable fee-hike rate and preferred rehabilitation rate in terms of minimizing either the infrastructure condition efficiency, as infrastructure BPI or the water TotalEx efficiency, as financial BPI have the same shape. In other words, both indicators can be optimized simultaneously by adjusting the two policy levers: 1) allowable fee-hike rate, and 2) preferred network rehabilitation rate for a given cash reserve. In summary, water utilities should select the optimal combinations of allowable fee hike and preferred rehabilitation rates that are on the boundary of the blue-contour region which enables them to sustainably achieve the stated targets over the life-cycle of water mains.

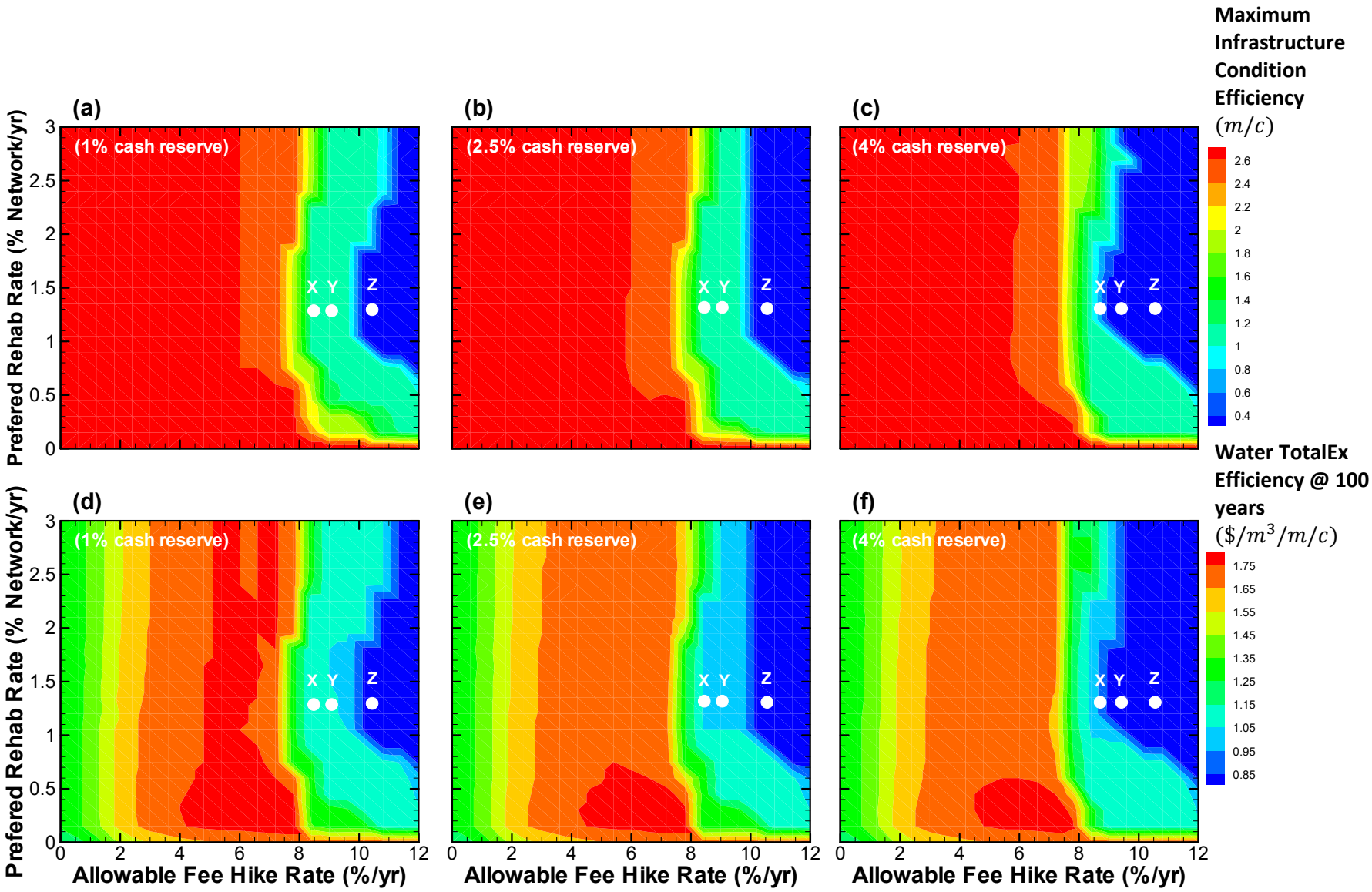


Figure 3.9**:** Impact of allowable fee hike and preferred rehabilitation rates on infrastructure condition efficiency and water TotalEx efficiency.

3.8 Conclusions

Based on this study, the following conclusions can be drawn:

1- An advanced system dynamics (SD) model is developed to forecast the future behaviour of water distribution networks.
2- The output of the advanced system dynamics model is then used to demonstrate the first known application of the entire benchmarking performance indicators (BPI's) for water distribution networks developed in Chapter 2.
3- An implementation framework for asset management strategy of water distribution networks is developed comprised of three decision-making layers: 1) visions & values, 2) function (i.e., advanced SD model), and 3) performance (i.e., BPI's).
4- Benchmarking results indicate that all three water utilities can sustainably meet the strategic targets established in the visions and values layer of the asset management strategy over the benchmarking period.
5- The "optimal" combinations of allowable fee hike and rehabilitation rates along with a capital reserving management strategy (i.e., cash reserve) will allow water utilities to have sufficient funds to meet their strategic targets.

Chapter 4
Benchmarking Asset Management Strategy of Wastewater Collection Networks

4.1 Overview

This study develops an implementation framework for asset management strategy of wastewater collection networks comprised of three decision-making layers: 1) "visions & values", 2) "function", and 3) "performance". This study also demonstrates the first known application of the entire set of benchmarking performance indicators for wastewater collection network established in Chapter 2, using the outputs of the advanced system dynamics model of this study. The asset management strategy framework is implemented and validated through demonstration of functionality and value by using the wastewater collection network of three utilities in Ontario, Canada to drive management simulations. A borrowing management strategy is used to benchmark the utilities against each other in terms of infrastructure, socio-political, and financial performance over a 100-year benchmarking period. Results demonstrate that wastewater collection networks can be benchmarked and compared using the benchmarking performance indicators to achieve their strategic targets over the life cycle of the system. The application of the entire BPI's demonstrates the complexity of wastewater collection system and allows a better understanding of the total system responses. It is found that a borrowing management strategy can enable the utility to accelerate capital works and reduces the volume of inflow and infiltration and its associated expenses over the life cycle of the assets. The impact of maximum debt capacity on two infrastructure and financial benchmarking performance indicators are also investigated to explore the "optimal" combination of allowable fee hike and preferred rehabilitation rates, using contour plots. Furthermore, a business case for asset management of wastewater collection networks using a borrowing management strategy is developed to explore the "optimal" combination of allowable fee-hike and rehabilitation rates, using developed inflow and infiltration expenditures ($I\&IEx$) saving ratio contour plots. The results indicate that a borrowing management strategy competes as long as the combinations of allowable fee-hike and preferred rehabilitation rates lead to a positive value of $I\&IEx$ saving ratio.

4.2 Introduction

Efforts have been made to adopt an asset management culture in the different parts of world. The Australian Accounting Standard (AAS) statement 27, issued in 1993, requires local governments to report on the current value and rate of consumption of their infrastructure assets. Similarly, the United States Governmental Accounting Standards Board (GASB) statement 34, issued in 1999 (Board 1999) and the Canadian Public Sector Accounting Board (PSAB) statement 3150, issued in 2009 (PSAB-3150 2009) require local governments to report all tangible assets along with their depreciation on financial statements. In 2004, the British Standard Institute published BSI PAS 55 that specifies requirements for 28 aspects of good practice asset management (Woodhouse 2010). This was updated and reissued in 2008 (PAS 2008) and eventually generalized in the ISO Standards (ISO 55000, 55001 & 55002) in 2014 (ISO 2014).

The above mentioned statements and standards provide general, but not asset specific, guidelines to generally implement a good asset management practice. Researchers developed system dynamics (SD) models for financially sustainable management of water distribution and wastewater collection systems over the life cycle (50+ years) of assets (Rehan et al. 2013; Rehan et al. 2014a). To some extent, these models can be used to determine two of the interconnected decision-making layers for asset management strategy (Woodhouse 2010): 1) to find out 'Where do we want to go?' and 2) to find out 'How do we get there?', as noted in Section 3.2 of Chapter 3. The benchmarking performance indicators (BPI's) proposed in Chapter 2 address the third interconnected decision-making layer for asset management strategy of wastewater collection networks: 3) to find out 'How are we doing?' (Woodhouse 2010), as noted in Section 3.2 of Chapter 3.

In Chapter 3, an implementation framework comprised of three decision-making layers of visions & values, function, and performance is developed for asset management strategy of water distribution networks. The visions & values layer is set according to the established concepts of strategic targets, policy levers, sustainability and life cycle. The function layer uses a system dynamics model based on advancements made to overcome the limitation associated with the Rehan et al. (2013) SD model, and the performance layer applies the entire set of BPI's developed by in Chapter 2 for water distribution networks. Despite these aforementioned advances, Chapters 2 and 3 are restricted to only water main benchmarking performance indicators in the evaluation and not constituted BPI's developed for

wastewater collection network. In addition, Rehan et al. (2014a) system dynamics model was restricted to some limitations as described in Section 4.2 of this Chapter.

This chapter: 1) develops an implementation framework for asset management strategy of wastewater collection networks comprised of three decision-making layers: "visions & values", "function", and "performance"; 2) improves the wastewater collection SD model developed by Rehan et al. (2014a) to use the output of the advanced model for wastewater BPI's; and 3) demonstrates the application of the entire set of BPI's for wastewater collection network established in Chapter 2 using the advanced system dynamics model of this study to benchmark and compare wastewater utilities' performances against each other. Moreover, derivative BPI's are developed to present a business case justifying the borrowing is a least total cost strategy based on the premise that the borrowing management strategy enables the utility to accelerate capital expenditures, which then improves the internal condition grade of sewer pipes. This management practice helps the utility to significantly mitigate the system's inflow and infiltration ($I\&I$) and reduces total expenses. In fact, savings on $I\&I$ are bigger than debt expenditures for a wide range of interest rates.

The merit of the proposed implementation framework for asset management strategy of wastewater collection networks are demonstrated using outputs from the advanced SD model of this study and BPI's developed in Chapter 2, and validated using data from three wastewater collection networks in Southern Ontario, Canada.

4.3 Implementation Framework of Asset Management Strategy

This study adopts the implementation framework for asset management strategy of water distribution networks presented in Chapter 3, Figure 3.1 to develop similar implementation framework for asset management strategy of wastewater collection networks.

4.3.1 Visions & Values Layer

The visions & values layer is made as identical as the visions and values layer for asset management strategy of water distribution networks presented in Chapter 3 which is set according to the established concepts of strategic targets, policy levers, sustainability and life cycle. The strategic targets and policy levers for asset management of wastewater collection networks are presented in Table 4.1 and Table 4.2, respectively.

Table 4.1: Strategic targets for asset management strategy of wastewater collection network

No.	Strategic Target	Description	Unit
1	$Min\ (infrastructure\ conditon\ efficiency)$	Minimizes length of pipes over design life ($\mathbb{D}$), *m* (i.e., pipes in ICG 5) per capita, *c*.	(m/c)
2	$Min\ (I\&I)$	The value of zero indicates no inflow & infiltration ($I\&I$) exist in the system.	$(m^3)\ or\ (litre)$
3	$Min\ (liability)$	$(\frac{Liabilities\ (\$)}{Assets\ (\$)}) = 0,$ the value of zero indicates that the water utility has no liability (liability-asset ratio is zero).	$(-)$
4	$Min\ (wasewater\ TotalEx\ efficiency)$	Minimizes wastewater total expenditures divided by treated water per length of network per capita.	$(\$/m^3/m/c)$

Table 4.2: Policy levers for asset management strategy of wastewater collection network

No.	Policy lever	Description	Unit
1	Preferred network rehabilitation rate	Percentage of total network length to be rehabilitated/replaced each year.	$(\%/year)$
2	Debt capacity	Maximum allowable debt as percentage of total revenue	(%)
3	Maximum acceptable fraction of highly deteriorated pipes	Percentage of pipes in ICG 5	(%)
4	Desired elimination period for highly deteriorated pipes	Elimination period for pipes in ICG 5	$(year)$
5	Allowable fee-hike rate	The maximum allowable increase in user fee per year	$(\%/year)$
6	Desired cash reserve	Percentage of total network asset value	(%)

4.3.2 Function Layer

The function layer uses the advanced system dynamics model of this study, as presented in Section 4.4, to achieve the visions & values of the utility. The system dynamics model explicitly models the feedback mechanisms among various components of the wastewater collection network. The outputs of the advanced system dynamics model are used to simulate and forecast the future performance of the system.

4.3.3 Performance Layer

Chapter 2 develops a series of benchmarking performance indicators for wastewater collection networks (see Section 2.4). These BPI's are organized into three main categories: 1) infrastructure; 2) socio-political; and 3) financial.

Physical infrastructure BPI's measure the performance of wastewater collection infrastructure assets in terms of 1) Infrastructure Efficiency which is the network pipeline length divided by the service population (m/c) , 2) Infrastructure Density which is the network pipeline length divided by the area serviced by the water utility (m/m^2); 3) Infrastructure Condition Ratio is length of pipes in Internal Condition Grade $(IC\ )$ five divided by total network length (m/m); 4) Infrastructure Condition Efficiency is the length of ICG 5 pipes divided by population served by utility; 5) Rehabilitation Efficiency is the percentage of actual rehabilitation rate (Rr) to target rate per year; and, 6) I&I Efficiency is total volume of inflow and infiltration $(I\&I)$ divided by total network length per population served by utility over the benchmarking period.

Socio-political performance of wastewater collection infrastructure assets is benchmarked using three indicators, as noted in Section 2.4.2: 1) Fee Hike Ratio is the percentage of current fee hike (FH) to allowable fee hike per year; 2) Wastewater Network Efficiency is the ratio of wastewater treated (WWT) to metered water; and, 3) Inflow and Infiltration $(I\&I)$ Ratio is the ratio of inflow and infiltration to metered water.

Financial performance is measured and enumerated in terms of the following eight BPI's: 1) Wastewater TotalEx Efficiency is total wastewater collection expenditures divided by wastewater treated over the benchmarking period per network length per capita; 2) Wastewater OpEx Efficiency is operational expenditures divided by wastewater treated over the benchmarking period per network length per capita; 3) Wastewater CapEx Efficiency is capital expenditures divided by wastewater treated over the benchmarking period per network length per capita; 4) Non-RevenueEx Efficiency is inflow and infiltration expenditures divided by wastewater treated over the benchmarking period per network length per capita; 5) Wastewater Debt Ratio is debt divided by wastewater treated over the benchmarking period per network length per capita; 6) Liability-Asset Ratio measures the percentage of liabilities to asset; 7) OpEx Ratio measures the ratio of operational expenditures over revenue; and, 8) CapEx Ratio measures the ratio of capital expenditures over revenue.

All of the aforementioned benchmarking performance indicators conform to the established concepts of strategic targets, policy levers, life cycle, and sustainability. These indicators are normalized to allow wastewater utilities to benchmark themselves against other wastewater utilities regardless of their scale. The system dynamics model developed by Rehan et al. (2014a) is improved to demonstrate the functionality of the wastewater BPI's using the outputs of the advanced wastewater system dynamics model.

4.4 System Dynamics Model for Wastewater Collection Network

Rehan et al. (2014a) developed a system dynamics model to understand the complex interaction that exists among physical, finance and consumers sectors of an urban wastewater collection system. A review of their model reveals some limitations such as "present" versus "future" value. Moreover, in a separate study, Rehan et al. (2014b) implemented their model for a synthesized utility data. This section first addresses the limitation associated with Rehan et al. (2014a) system dynamics model and then, improvements made to create an advanced strategic-level asset management model corresponding to three utility's wastewater collection network located in Southern Ontario, Canada. The advanced SD model of this study explicitly models the feedback mechanisms among the infrastructure, finance, and socio-political sectors and allows tracking of BPI's.

4.4.1 Infrastructure sector

This sector represents the inventory of pipes for the wastewater collection network. The physical condition of the wastewater collection network is divided into five variables (stocks) based upon the internal condition of the pipes using the UK's Water Research Centre rating system proposed in the fourth edition of the Sewerage Rehabilitation Manual (WRc 2001). Pipes in a given stock transfer to the next condition stock through an inflow (i.e., deterioration modeling). The condition assessment data for the wastewater collection network of each of the three utilities is collected. Moreover, the inventory of sewer pipes for the three wastewater utilities is collected and simulated in the infrastructure sector of the advanced system dynamics model.

Sewage generated from different classes of customers are also incorporated into the measurements of the annual total flow, hence new sewage flow is measured not only based upon the sewage generated

from the residential sector, but also the swage generated from different classes of customers such as commercial and industrial.

4.4.2 Finance sector

This sector describes the network's financial condition and includes revenues, expenses, fund balance, sewage fee, debt, etc. Rehan et al. (2014a) assumes that the unit costs are constant over the simulation period. Thus, the rate of appreciation of costs (inflation rate) is equal to the project discount rate needed to discount all costs to present value. This study incorporates inflation into the finance sector. Therefore, all costs are calculated as "future value" as the various unit costs inflate over the simulation period.

The customers of a water utility are required to pay for the treatment and collection costs associated with the amount of generated sewage flow based upon their volume of water consumption (Equation 4.1).

$$WWC_{VC}(t) = Sf(t) \times \sum_{cc} MW(t) \qquad (4.1)$$

where, WWC wastewater collection; VC variable cost (\$); Sf sewage fee ($\$/m^3$); MW Metered water (m^3); t time; cc classes of customers include residential, commercial and institutional. They are also required to pay a fixed cost for the services provided to them regardless of the amount of consumed water, with the this fixed cost being a function of the size of service connections (pipe's diameter) for the wastewater collection pipe (Equation 4.2).

$$WWC_{FC}(t) = \sum_{d=1}^{d=Nmm} [SSC_d(t) \times NSC_d(t)] \quad (4.2)$$

where, FC fixed cost; d diameter of service connection for $d = 15mm, 19mm, \dots, N$; N maximum diameter of service connection; SSC sewage service charges; NSC number of service connection. This study incorporates sewage service charges into the calculations of total revenue collected from the customers. Therefore, the wastewater collection revenue (WWC_{RV}) is measured as the sum of variable and fixed costs as:

$$WWC_{RV}(t) = WWC_{VC}(t) + WWC_{FC}(t) = [Sf(t) \times \sum_{cc} MW(t)] + \sum_{d=15mm}^{d=Nmm} [SSC_d(t) \times NSC_d(t)] \quad (4.3)$$

Developers are also required to pay one-time development chargers (DC) for the expenditures associated with the extension of wastewater collection networks to the new developed areas. Development charges

can be considered as a source of income for a wastewater utility, but revenue collected from customers in the form of variable and fixed costs is a major source of income. This study incorporates development charges into the finance sector as a source of total income to pay capital expenditures. Thus, the fund balance (FB) is measured given:

$$WWC_{FB}(t) = WWC_{Inc}(t) - WWCEx(t)$$

$$WWC_{FB}(t) = [WWC_{RV}(t) + WWC_{IE}(t) + WWC_{DC}(t)] - [CapEx\ (t) + OpEx(t) + IntEx(t)]$$

$$WWC_{FB}(t) = \begin{bmatrix} \left\{Sf(t) \times \sum_{cc} MW(t)\right\} \\ + \left\{\sum_{d=15m}^{d=Nmm} SSC_d\,(t) \times NSC_d(t)\right\} \\ +\{WWD_{IE}(t)\} + \{WWD_{DC}(t)\} \end{bmatrix} - [CapEx(t) + OpEx(t) + IntEx(t)]$$

Note: $for\ WWC_{IE}(t),\ If\ WWC_{FB}(t) > 0\ Then\ WWC_{IE}(t) = WWC_{FB}(t) \times Sr(t)$

$$Else\ WWC_{IE}(t) = 0 \qquad (4.4)$$

where, Inc income; IE interest earnings ($) is a source of income accrued on the wastewater utility's positive fund balance (cash reserves); Sr saving rate ($\%/year$); $CapEx$ capital expenditures ($); $OpEx$ operational expenditures ($); $IntEx$ interest expenditures ($).

4.4.3 Socio-political sector

This sector presents the consumption behavior of customers in response to sewage fee oscillations and level of service delivered to them. In Rehan et al.'s (2014a) model, price elasticity of water demand is modeled as a constant parameter. In this study, price elasticity of demand is modeled as a variable parameter based on different classes of customers, as depicted and noted in Chapter 3.

4.5 Asset Management Strategy Implementation

Three medium-sized utilities located in Southern Ontario, Canada, arbitrarily called X, Y and Z are used to demonstrate the application of the entire wastewater collection network benchmarking performance indicators developed in Chapter 2, using the advanced system dynamics model of this study. These indicators are used to benchmark and compare the infrastructure, socio-political, and financial

performance of the utilities. Demographic data for each utility include population, total length of wastewater collection pipes along with the two infrastructure BPI's of infrastructure efficiency and density are given in Table 4.3. These networks comprised of various categories of pipes made of asbestos cement (AC), polyvinyl chloride (PVC), concrete and vitrified clay (VC).

Table 4.3**:** Demographic information of wastewater utilities

Wastewater Utility	**X**	**Y**	**Z**
Population $[c]$	120,000	130,000	83,000
Wastewater pipe length $[m]$	341,000	503,000	412,000
Infrastructure Efficiency $[m/c]$	2.84	3.87	4.96
Infrastructure Density $[m/m^2]$	5.3×10^{-3}	4.6×10^{-3}	2.0×10^{-3}

4.5.1 Parameters and Variables

Strategic targets and policy levers controlling theses targets are made as identical as possible between each utility under the assumption they will have similar preferences to meet the utility's stakeholders needs using a borrowing management strategy over a 100-year life cycle.

The preferred network rehabilitation rate (policy lever 1) is set at 1.3% of the network per year to reflect desired utilities practice and target rate recommended by the Canadian Infrastructure Report Card (2016). Policy lever 2 allows wastewater utilities to borrow (i.e., issuing debt) up to 12.5% of their annual revenue to accelerate the capital expenditures. Policy lever 3 is set at 10%, indicating that the utility will allow up to 10% of the length of the pipes in its wastewater collection network to be in the worst structural condition (i.e., ICG 5). If the 10% threshold is exceeded, a network rehabilitation rate higher than the preferred rate of 1.3% is required to eliminate deteriorated pipes in the network within the elimination period of 10 years (Policy lever 4). Through trial and error, the optimal values of allowable sewage fee-hike rates (policy lever 5) are found to be 7% per annum for all utilities.

The current sewage fees that utilities charge their customers per cubic meter of treated wastewater are $\$1.91, \$1.76\ and\ \$0.99/m^3$ for utilities X, Y and Z, respectively. The current unit cost of wastewater

treatment is reported $\$0.77/m^3$ for the three utilities. Typical average daily water consumption in the local region is 280 liters per capita per day ($lpcd$) for utilities X and Z and 322 $lpcd$ for utility Y, and are used as the initial water demand for this study. The minimum water demand for the three utilities is assumed to be 150 $lpcd$.

The current unit cost for rehabilitating pipes in condition grade 4 (ICG 4) is reported to be $600 per meter and for pipes in condition grade 5 (ICG 5) is set at $1000 per meter for the three utilities. The unit operation and maintenance costs and inflow and infiltration rates are calculated in a manner identical to Rehan et al. (2014b). The 5.52% per annum inflation rate reported by Younis et al. (2016) for wastewater pipe construction projects is used in this study to inflate the unit cost of pipe renewal($\$/m$), the unit cost of pipe maintenance ($\$/m/year$), and the unit price of treated wastewater ($\$/m^3$). Household income is inflated over the benchmarking period at a rate of 2.4% per annum based on the customer price index (CPI) of Canada (Statistics Canada 2014).

4.6 Results

The borrowing management strategy is compared over a 100-year benchmarking period using three categories of BPI's developed in Chapter 2 for the wastewater collection network: 1) infrastructure, 2) socio-political, and 3) financial. Benchmarking results for the three wastewater utilities are illustrated in Figures 4.1 to 4.3.

4.6.1 Infrastructure performance indicators

This category measures the infrastructure performance of wastewater collection network. The BPI's of infrastructure efficiency and density for each utility are provided in Table 4.1. For this study, the wastewater network length, population and area serviced by the utility are assumed to be constant over the benchmarking period. Therefore, the infrastructure efficiency BPI is $3.0, 3.85\ and\ 5.42\ m/c$, for utilities X, Y and Z, respectively, while the infrastructure density BPI is $5.3 \times 10^{-3}, 4.6 \times 10^{-3}\ and\ 2.0 \times 10^{-3}$ for utilities X, Y and Z, respectively, as noted in Table 4.1. The three BPI's of a) infrastructure condition efficiency (m/c), b) rehabilitation efficiency ($\%/yr$), and c) $I\&I$ efficiency ($l/m/c/yr$) are illustrated with wastewater utilities X, Y and Z in Figure 4.1.

Results indicate that the three utilities meet the strategic target of $Min\ (m/c)$, the BPI of infrastructure condition efficiency, with the controlling policy lever 1 (i.e., preferred rehab rate of 1.3% of the network

per year), policy lever 3 (i.e., no more than 10% of pipes in ICG 5), and policy lever 4 (i.e., eliminating period of 10 years for pipes in ICG 5). In addition, the strategic target of $Min\ (I\&I)$ is met for the three utilities, as illustrated in Figure 4.1c. Therefore, all three wastewater utilities sustainably maintain these targets over the life cycle of the infrastructure.

Figure 4.1a shows the infrastructure condition efficiency (i.e., length of ICG 5 pipes per capita) for the three wastewater utilities. For utility X, the infrastructure condition efficiency starts with a value of $0.04\ m/c$, increases to $0.22\ m/c$ at 10 years due to ICG 4 pipes moving to ICG 5, then decreases to reach the value of $0.0\ m/c$ at 45 years where it remains to the end of benchmarking period. For utilities Y and Z, the fraction of highly deteriorated pipes starts with a value of 0.24 and $0.46\ m/c$, respectively, followed by a decline to reach the value of $0.0\ m/c$ at 45 years and to the end of the benchmarking period, as shown in Figure 4.1a.

Figure 4.1b shows the rehabilitation efficiency BPI. The result of this BPI indicates that the strategic target of $Min\ (m/c)$, length of highly deteriorated pipes (i.e., ICG 5 pipes) per capita is met using the controlling policy lever of preferred rehabilitating rate of 1.3% of the network length per year. The value above 100 percent indicates that the acceptable fraction of deteriorated pipes (policy lever 3) exceeds its maximum threshold of 10%. Hence, the actual network rehabilitation rate is higher than the preferred rate of 1.3% (policy lever 1) in order to eliminate deteriorated pipes in the network within the elimination period of 10 years (Policy lever 4).

For utility X, the rehabilitation efficiency starts with a value of 100 percent and remains constant for 55 years due to ICG 5 pipes. Thereafter, there is a sudden decline to reach the minimum value of 78 percent at 55 years, and then is followed by a continuous increase to 90 percent at 80 years due to ageing ICG 4 pipes, and remains constant to the end of the benchmarking period (Figure 4.1b). For utility Y, the rehabilitation efficiency starts with a value of 100 percent, climbs to 154 percent at 12 years due to ICG 5 pipes backlogs, followed by a sudden decline to 65 percent at 13 years, and a continuous climb to 90 percent at 80 years due to ICG 4 pipes aging to ICG 5, and remains constant to the end of the benchmarking period (Figure 4.1b). For water utility Z the rehabilitation efficiency starts with a value of 100 percent, followed by a sudden climb to 124 percent at 38 years due to increase in the volume of ICG 5 pipes, and continues to increase to reach its maximum value of 152 percent at 43 years, followed by a sudden decline to 83 percent at 45 years, and then followed by a continues climb to 90 percent at 80 years

due to ICG 4 pipes aging to ICG 5, and remains constant to the end of the benchmarking period (Figure 4.1b).

Figure 4.1c depicts the BPI of $I\&I$ efficiency by measuring the volume of inflow and infiltration ($I\&I$) per meter per capita over the benchmarking period ($l/m\,/c/yr$). It shows the initial values of $0.08, 0.07\ and\ 0.06\ \ l \times 10^3/m\,/c/yr$ for utilities X, Y and Z, respectively This performance indicator declines for the three utilities implying that they all achieve the strategic target of minimizing ($I\&I$) over the life-cycle of the infrastructure.

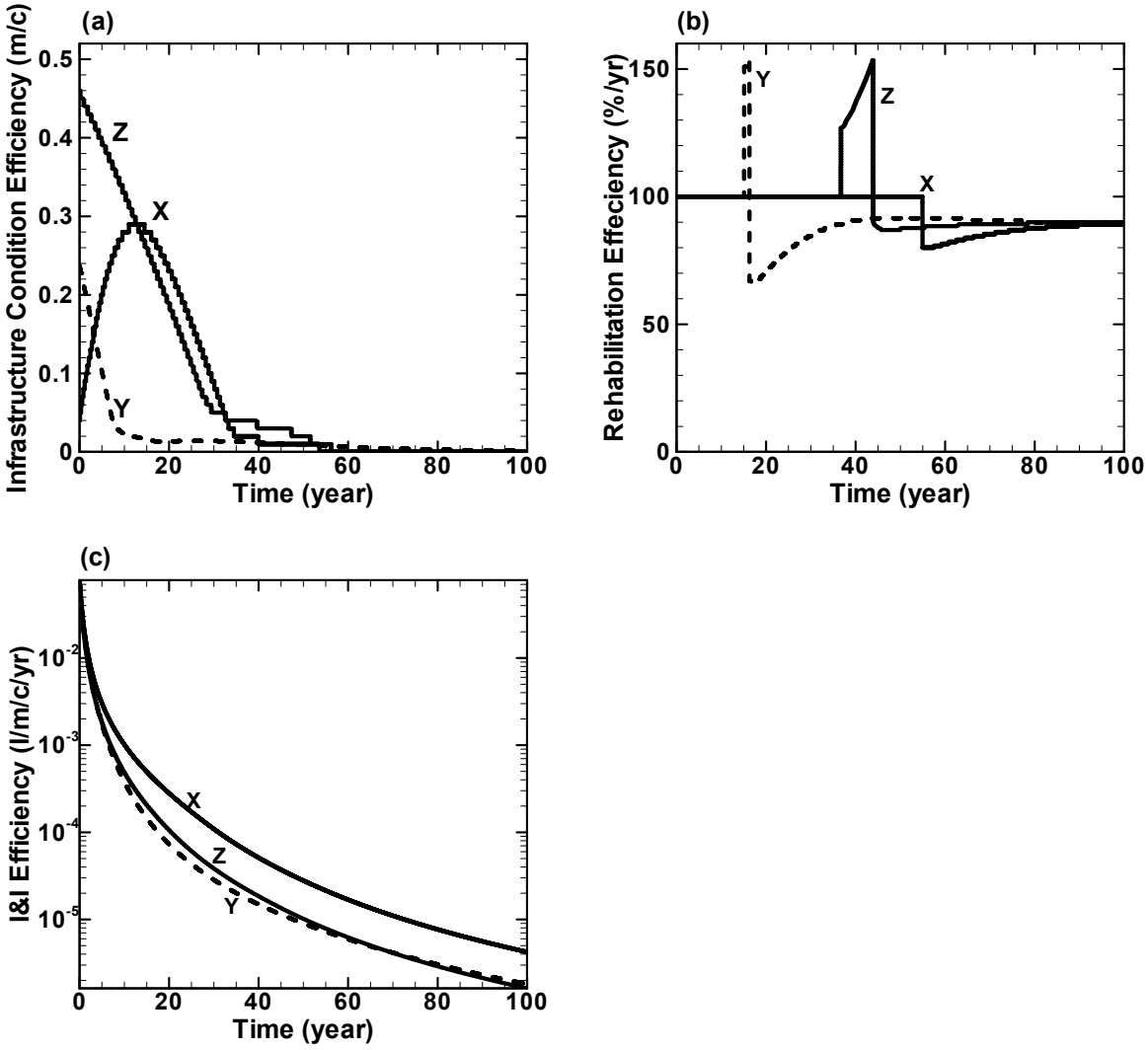


Figure 4.1: Wastewater infrastructure performance indicators over a 100-year benchmarking period for utilities X, Y and Z.

4.6.2 Socio-political performance Indicators

This category measures the socio-political performance of three wastewater utilities in terms of a) fee hike ratio ($\%/yr$), b) wastewater network efficiency (m^3/m^3), and c) inflow and infiltration ($I\&I$) ratio (m^3/m^3). The results of this category show that the three utilities achieve the stated strategic targets of $Min\ (I\&I)$, as shown in Figures 4.2b and 4.2c.

Figure 4.2a shows the fee hike ratio BPI for the three wastewater utilities. This BPI is measured as a percentage of current to allowable fee-hike rates over the benchmarking period. A value of unity indicates that the current fee hike rate equals to the allowable fee-hike rate. Fee hike ratio BPI shows some oscillations over the benchmarking period due to available funds required to pay for wastewater expenditures.

The BPI of wastewater network efficiency, as depicted in Figure 4.2b, shows a declining trend for the three utilities. The optimum value is assumed to be 0.9 out of 1.0 based on the assumption that 0.1 (i.e., 10%) of metered water is non-consumptive water used by customers and not retuned back to the wastewater collection system (for instance, water used in watering lawns and evaporated from pools). Hence, a value of 0.9 indicates that the wastewater network is 100% efficient and that treated wastewater equals metered water (i.e., no $I\&I$ exist in the system). The wastewater network efficiency BPI starts with a value of 1.0, 0.95 and 1.15 for utilities X, Y and Z, respectively, followed by a decline to their minimum values of 0.92, 0.94 and 0.96, respectively at the end of benchmarking period.

Figure 4.2c shows the ratio of $I\&I$ to metered water over the benchmarking period. The optimum value for this performance indicator is 0.0 and indicates that there is no $I\&I$ in the system. Utility Z has the highest $I\&I$ ratio over the benchmarking period, shown in Figure 4.2c due to the fraction of its highly deteriorated pipes (Figure 4.1a) compared to the other two utilities. Ultimately, as simulated by the model, the three utilities achieve the strategic targets of $Min\ (I\&I)$, minimize inflow and infiltration over the benchmarking period.

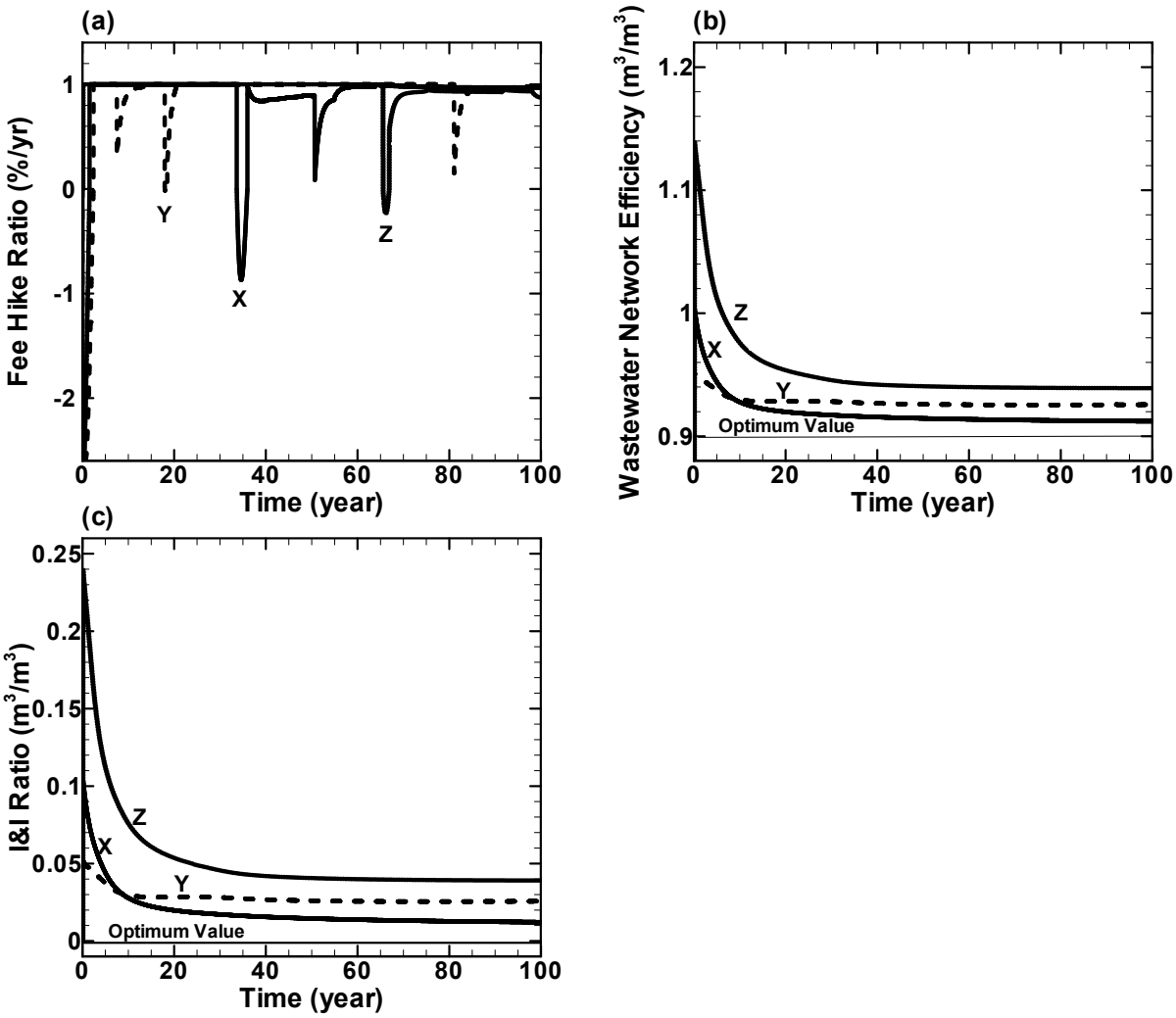


Figure 4.2: Wastewater socio-political performance indicators over a 100-year benchmarking period for utilities X, Y and Z.

4.6.3 Financial Performance Indicators

Financial performance of the three utilities' wastewater collection networks is benchmarked using the eight BPI's for wastewater networks established in Chapter 2. The benchmarking results, as illustrated in Figure 4.3, indicate that the three utilities meet the strategic targets of:
$Min\ (wastewater\ TotalEx\ efficiency)$, $Min\ (I\&I)$, and $Min\ (liability)$.

Residents of utility X spend more dollars per cubic meter of treated wastewater per length of network per capita in the first 60 years compared to the other utilities, as depicted in Figure 4.3a. This is due to its higher value of non-RevenueEx efficiency over the entire benchmarking period (Figure 4.3b), and its highest wastewater debt ratio for nearly 30 years (Figure 4.3g) compared to the other utilities. In contrast, residents of utility Y experience the least wastewater TotalEx efficiency values over the benchmarking period. Wastewater TotalEx efficiency starts with a value of $\$0.25, \$0.17 and \$0.22/m^3/m/c$ for utilities X, Y and Z, respectively, followed by a linear increase to converge to the value of $\$0.35, \$0.25 \ and \ \$0.35/m^3/m/c$ for utilities X, Y and Z, respectively (Figure 4.3a). In summary, the three utilities ultimately achieve similar behaviour over the entire benchmarking period with the spread in their wastewater TotalEx efficiency never separating by more than \$0.19 $m^3/m/c$. The spread persists due to the assumption of constant population and network length combined with the allowable fee-hike rates that permits each utility to have sufficient revenue to meet expenses over the benchmarking period. In summary, the three utilities achieve the strategic targets of Min ($\$/m^3/m/c$), minimizes wastewater total expenditures divided by treated wastewater per length of network per capita.

Figure 4.3b shows the non-RevenueEx efficiency BPI that is measured in terms of $I\&I$ expenditures over treated wastewater per meter of network length per capita. It starts with the initial values of $\$0.06, \$0.05 \ and \ \$0.04/m^3/m/c$ for utilities X, Y and Z, respectively. The results show similar declining trend for utilities Y and Z to the end of the benchmarking period to reach their minimum values of $\$0.03 \ and \ \$0.02/m^3/m/c$. For utility X, the non-RevnueEx efficiency increases to reach its maximum value $\$1.05/m^3/m/c$ at 20 years. Thereafter, it declines toward the end of the benchmarking period and reaches a value of $\$0.06/m^3/m/c$ (Figure 4.3b). In summary, the three utilities meet the strategic targets of 1) Min ($wastewater \ TotalEx \ efficiency$) and 2) $Min(I\&I)$ over the benchmarking period.

Figure 4.3c shows the OpEx efficiency BPI for the three wastewater utilities that is measured in terms of operational expenditures over treated wastewater per meter of network length per capita. The OpEx efficiency BPI starts with initial values of $\$0.08, \$0.06 \ and \ \$0.08/m^3/m/c$ for utilities X, Y and Z, respectively, and continues to increase to the end of the benchmarking period to reach the value of $\$0.14, \$0.12 \ and \ \$0.16/m^3/m/c$ for utilities X, Y and Z, respectively (Figure 4.3c).

Figure 4.3d shows the CapEx efficiency BPI in terms of capital expenditures over treated wastewater per meter of network length per capita. The CapEx efficiency BPI starts with the initial values of

$\$0.11, \$0.05\ and\ \$0.11/m^3/m/c$ for utilities X, Y and Z, respectively (Figure 4.3d). The results indicate the same trend for all utilities beyond 40-50 years with the final values of $\$0.13, \$0.022\ and\ \$0.16/m^3/m/c$ (Figure 4.3d). Utility Y experiences the least dollars divided by cubic meter of treated wastewater per meter per capita for its capital works compared to the other utilities due to its youngest inventory of pipes (Figure 4.1a). Ultimately, all utilities achieve similar behaviour over the entire benchmarking period with the spread in their CapEx efficiency never separating by more than approximately $\$0.15\ m^3/m/c$, respectively. In summary, the three utilities achieve the strategic targets of $Min\ (wastewater\ TotalEx\ efficiency)$ by minimizing capital expenditures over treated wastewater per meter of network length per capita, and comply with the policy lever of no more than 10% of the network in ICG 5 pipes.

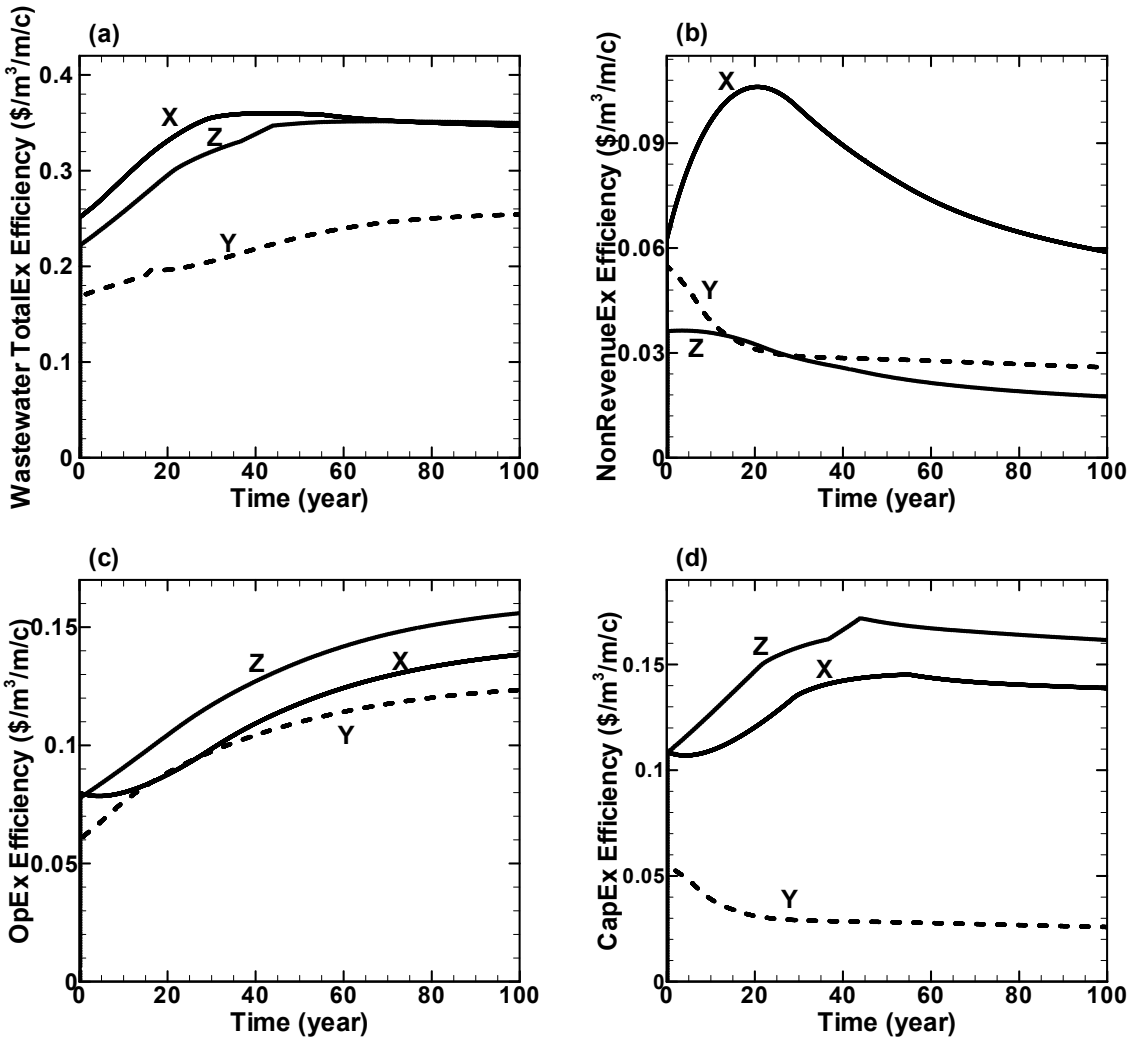
The OpEx ratio BPI determines whether a utility achieves its operational program targets by measuring the percentage of operational expenditures over the revenue, as noted in Chapter 2, Section 2.4.3. Figure 4.3e shows the OpEx ratio for the three wastewater utilities. The OpEx ratio starts with a value of 0.61, 0.63 and 0.70 for utilities X, Y and Z, respectively, and follows with some curvatures to the end of the benchmarking period to reach the values of 0.78, 0.79 and 0.68 percent for utilities X, Y and Z, respectively.

The CapEx ratio BPI determines whether a utility achieves its capital works targets by measuring the percentage of capital expenditures over the revenue, as noted in Chapter 2, Section 2.4.3. Water utility Z has the highest value of CapEx ratio over the benchmarking period (Figure 4.3f) due to highest fraction of ICG 5 pipes (Figure 4.3d). Therefore, it requires spending more funds on capital works to comply with the policy lever 3, no more than 10% of the network in ICG 5 pipes.

The wastewater debt efficiency BPI, as shown in Figure 4.3g measures the utility' debt expenditures divided by treated wastewater per meter of network length per capita ($\$/m^3/m/c$). This indicator starts with the initial value of $\$0.0/m^3/m/c$ for the three utilities , reaches the maximum values of $\$0.06, \$0.01\ and\ \$0.04/m^3/m/c$ at 12, 60 and 50 years for utilities X, Y and Z, respectfully, and declines to the end of the benchmarking period to reach the final values of $\$0.02, \$0.008\ and\ \$0.026/m^3/m/c$ for utilities X, Y and Z, respectfully.

The BPI of liability-asset ratio, as depicted in Figure 4h, is measured as a percentage of total liabilities relative to total assets for a utility, as described in Chapter 2, Section 2.4.3. This indicator starts with the

initial value of zero percent for all three wastewater utilities, follows by an increase to reach its maximum value of 3.5%, 2.8% and 2.4% for utilities X, Y and Z, respectively, and follows by a declining trend to the end of the benchmarking period to reach the value of 1.3%, 1.6% and 2.1% for utilities X, Y and Z, respectively.



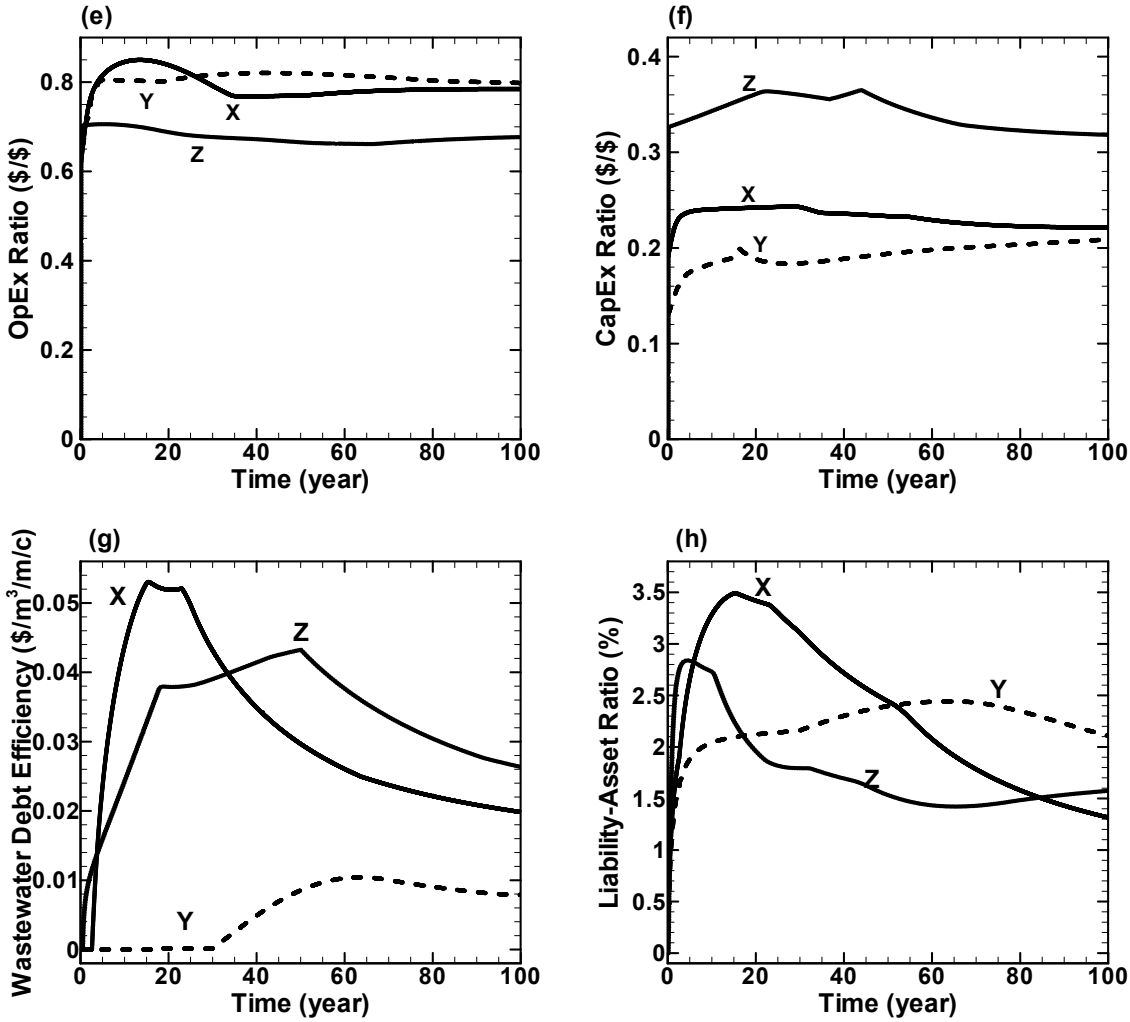


Figure 4.3: Wastewater financial performance indicators over a 100-year benchmarking period for utilities X, Y and Z.

4.7 Discussion

This study demonstrates the idea of how the application of the entire wastewater BPI's developed in Chapter 2 can be used by the utility's stakeholders to understand and track the complex non-linear behavior of their system's performance over the benchmarking period. The benchmarking results indicate that the three utilities can achieve their strategic targets using the controlling policy levers established in Table 4.1and Table 4.2, respectively.

The average wastewater debt efficiency BPI over the benchmarking period is $\$0.03, \$0.01\ and\ \$0.03/m^3/m/c$ for utilities X, Y and Z, respectively, and, the average non-RevenueEx efficiency BPI is $\$0.08, \$0.03\ and\ \$0.03/m^3/m/c$ for utilities X, Y and Z, respectively. Comparing the results of these two BPI's implies that a borrowing management strategy can enable the utility to significantly mitigate the volume of inflow and infiltration ($I\&I$) and reduces its associated costs over the benchmarking period.

The borrowing management strategy can provide sufficient funds for the utility to replace its existing backlog of deteriorated sewer pipes and to maintain network rehabilitation at the preferred rate of 1.3% of the network length per year (policy lever). As result of issuing debt, the utility's liability increases. On the other hand, capital works improve the average network condition and hence, increases the network assets monetary value. Ultimately the three utilities can achieve the strategic target of minimizing liability over the benchmarking period (Figure 4.3h).

The results show that the three utilities meet the stated strategic targets of 1) Min (infrastructure condition efficiency); 2) $Min\ (I\&I)$, the BPI's of $I\&I$ efficiency, wastewater network efficiency, $I\&I$ ratio and non-RevenueEx efficiency, 3) $Min\ (liability)$, the BPI of liability-asset ratio, and 4) $Min\ (wastewater\ TotalEx\ efficiency)$, minimize wastewater total expenditures divided by treated wastewater per length of network per capita. Therefore, the three utilities sustainably maintain these targets using the controlling policy levers noted in Table 4.2 over the benchmarking period.

4.7.1 Effect of interest rate spread on borrowing strategy

The previous simulations assessing the three wastewater utilities' BPI's involved an interest rate spread of 1.5% per annum in excess of risk free rate, with a maximum issuance debt capacity of 12.5% of annual revenue. Municipal governments in the province of Ontario, Canada can borrow at a typical spread of 1% per annum in excess of risk free rate established by Canada Bond. Additionally, the three utilities have an allowable fee-hike rate of 7% per annum with a 1.3% preferred network rehabilitation rate. A key issue within this chapter is to assess the business case of borrowing as a financial strategy to accelerate capital expenditures, thereby minimizing operation expenditures and hence the total cost of the wastewater network over its design life. The viability of this business case is dependent on the interests rate spread rate. Therefore, it is instructive to explore network management strategies over a broader range of two policy levers of 1) allowable fee-hike and 2) preferred network rehabilitation rates under interest rate

spread values of 0, 1.5, and 3% per annum. Clearly, an interest rate spread of 0% per annum is essentially "free" money whereby the Federal government provides a grant to the utility, with repayment tied to the Federal government's ability to raise capital. In contrast, an interest rate spread of 3% per annum is slightly in excess of what typical municipal bonds provide to investors within the US. An interest rate spread of 1.5% per annum is comparable to what Infrastructure Ontario attempts to offer to participating municipalities.

Within each scenario set, the allowable fee-hike rate is varied over a range of 0% to 12% per annum, and preferred network rehabilitation rate is varied over a range of 0% to 3% per annum with a unique maximum debt capacity of 12.5% of utility's annual revenue. It is assumed that allowable fee-hike rate in excess of 12% per annum is not a politically feasible strategy for the utility to sustain over the long run. Similarly, a capital works plan rehabilitating in excess of 3% of the network per year is assumed not feasible due to availability of physical and financial resources. Policy levers for the three scenario sets are provided in Table 4.4. The effect of interest rate spread is presented on two selected BPI's representing infrastructure and financial performance of utilities. The BPI of infrastructure condition efficiency (m/c) is selected for infrastructure performance, and the BPI of wastewater TotalEx efficiency ($\$/m^3/m/c$) is selected for financial performance of the utility over the benchmarking period.

Table 4.4: Policy levers for three scenario sets.

Policy Lever	Scenario 1	Scenario 2	Scenario 3
Interest rate spread (percent per annum)	0	1.5	3
Maximum acceptable fraction of ICG 5 pipes (% of network length)	10	10	10
Desired elimination period of ICG 5 pipes (years)	10	10	10
Allowable fee-hike rate (percent per year)	0 to 12	0 to 12	0 to 12
Preferred rehabilitation rate (% of network per year)	0 to 3	0 to 3	0 to 3

Figures 4.4a, 4.4b and 4.4c present the contours of maximum value of infrastructure condition efficiency BPI over the benchmarking period, for scenarios 1, 2 and 3 with 0, 1.5 and 3% per annum interest rate spread, respectively. These contours are the mean BPI values arising from the simulations (3,969 runs) for the three utilities. For comparative purposes, utilities X, Y and Z with the unique set of allowable fee hike and preferred network rehabilitation rates, as discussed in the previous section are illustrated with white dots on Figures 4.4a, 4.4b and 4.4c. Figures 4.4d, 4.4e and 4.4f show contours of

the wastewater TotalEx efficiency at 100 years, as measured in terms of cumulative total wastewater collection expenditures divided by cumulative treated wastewater per length of wastewater network per capita ($\$/m^3/m/c$) at100 years, for scenarios with 0, 1.5 and 3% per annum spread, respectively. These contours are also the mean BPI values arising from the simulations (3,969 runs) for the three utilities. Once again, for comparative purposes, utilities X, Y and Z are depicted with white dots on Figures 4.4d, 4.4e and 4.4f.

Figures 4.4a to 4.4c indicate that the maximum value of infrastructure condition efficiency BPI decreases as the allowable fee-hike rate increases to its maximum value. The results show no significant sensitivity to the maximum value of infrastructure condition efficiency as the preferred rehabilitation rate increase to its maximum value (Figures 4.4a to 4.4c). The results of Figures 4.4a to 4.4c show similar behavior with different spread of 0, 1.5 and 3% per annum. The least (m/c) region is shown with blue contour for spread of 0, 1.5 and 3% per annum. From a socio-political perspective, it is desirable for the utility to operate on boundary of the blue contour. The results of different spread rates indicate that the three utilities, as depicted with white dots on Figures 4.4a to 4.4c, operate on boundary or in the blue region. This means efficiency in terms of infrastructure condition for the three utilities with the unique allowable fee hike of 7% per annum, and 1.3% preferred network rehabilitation rate per annum.

Figures 4.4d to 4.4f indicate that the value of wastewater TotalEx efficiency, as a financial BPI, has the opposite trend relative to the infrastructure condition efficiency and increases as the allowable fee-hike rate increases over the benchmarking period. The least TotalEx efficiency region is shown with blue contour for spread of 0, 1.5 and 3% per annum. The results of Figures 4.4d to 4.4f indicate as spread increases from 0% to 3% per annum, the wastewater TotalEx efficiency shows similar behavior for all combinations of allowable fee-hike rate and rehabilitation rate. For the original scenarios of X, Y and Z, as shown with dots on Figures 4.4d to 4.4f, the results indicate that the three utilities operate on boundary of the orange-contour region.

The most important observation is that contours representing the “optimal” combination of allowable fee-hike and preferred rehabilitation rates in terms of minimizing either the infrastructure condition efficiency, as physical infrastructure BPI or the wastewater TotalEx efficiency, as the financial BPI has a different shape. The utility should select the optimal combinations of allowable fee-hike rate and preferred rehabilitation rate that are on boundary of the blue region or in the light blue region for the infrastructure condition efficiency, and the optimal combinations of allowable fee-hike rate and preferred

rehabilitation rate that are on boundary of the orange region or in the yellow region for the wastewater TotalEx efficiency. This can enable them to sustainably achieve the stated targets over the life-cycle of their infrastructure assets. It should be noted that utilities can select the optimal combinations of allowable fee-hike and preferred rehabilitation rates based upon their own preferences and stakeholders' objectives.

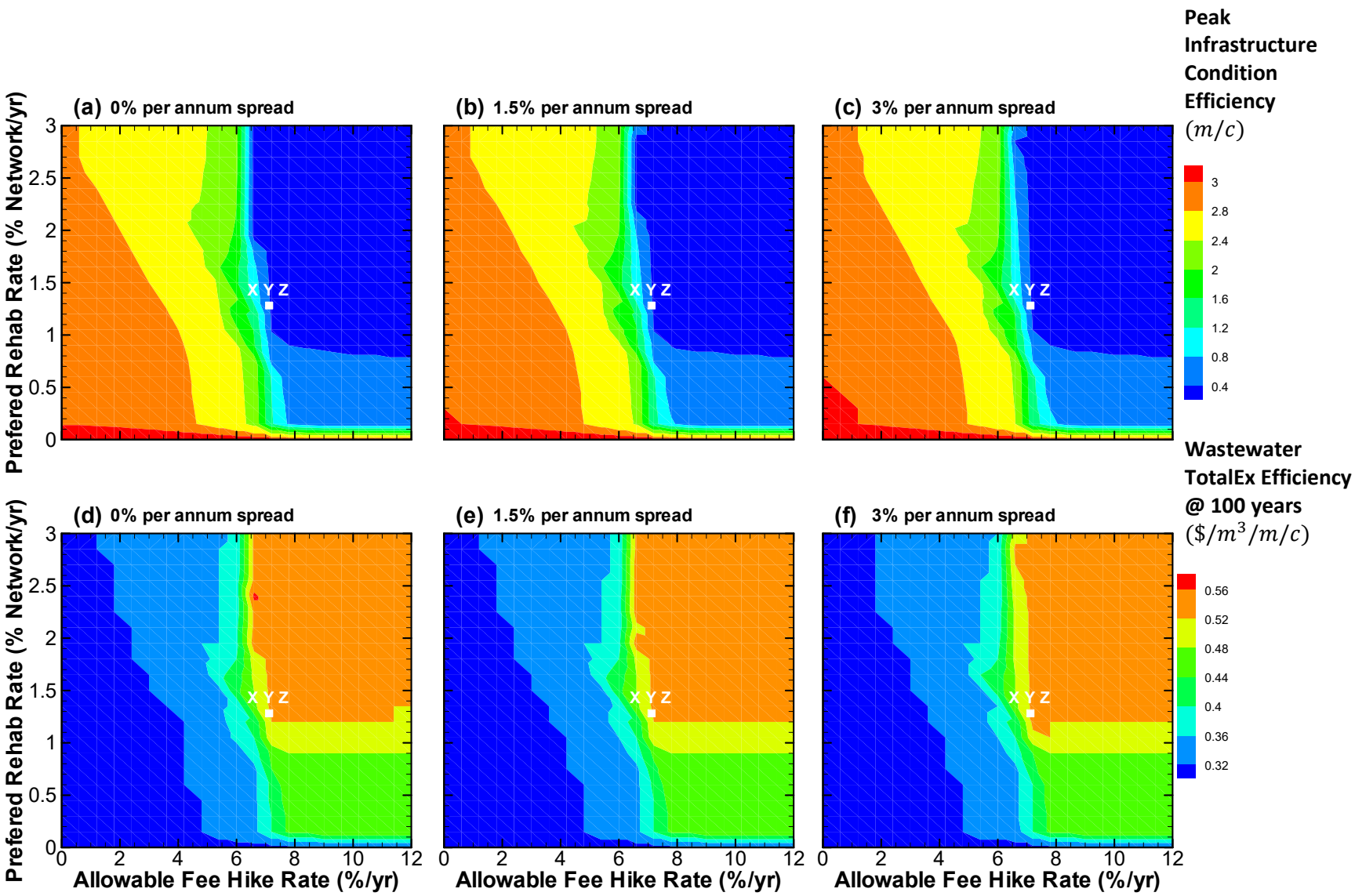


Figure 4.4: Impact of allowable fee hike and preferred rehabilitation rates on infrastructure condition efficiency and wastewater TotalEx efficiency

4.7.2 Business Case for Asset Management of Wastewater Collection Networks

This section presents a business case for asset management of wastewater collection networks using a borrowing management strategy. The innovation of this section is to illustrate how the previous BPI's can be rearranged to yield a derivative BPI metric: Inflow and infiltration expenditures ($I\&IEx$) saving ratio. The objective of this new BPI metric is to explore the benefits of a borrowing management strategy with the maximum debt capacity of Q% relative to a no borrowing (pay-as-you-go) management strategy (i.e., 0% debt capacity). The $I\&IEx$ saving ratio is given in Equation**Error! Reference source not found.** 4.5, and expresses the business case for borrowing by: subtracting $I\&IEx$ with Q% debt capacity and its associated interest expenditures ($IntEx$) from $I\&IEx$ with 0% debt capacity; and further normalized by $I\&IEx$ with 0% debt capacity. The derivative BPI is expressed as:

$$I\&IEx\ Saving\ Ratio\ (\%)\ = \frac{\sum_{t=0}^{T} I\&IEx(t)_{Dc=0\%}\times\Delta t-[\sum_{t=0}^{T}(I\&IEx(t)_{Dc=\mathrm{Q}}+IntE_{\ Dc=\mathrm{Q}})\times\Delta t]}{\sum_{t=0}^{T} I\&IEx_{Dc=0\%}\times\Delta t}\times 100 \qquad (4.5)$$

where, $I\&IEx$ = inflow and infiltration expenditures; Dc = Debt capacity (% of annual revenue per annum); Q = maximum debt capacity (% of annual revenue per annum); t = time (year); T= benchmarking period in years; Δt = time step. An $I\&IEx$ saving Ratio with a value greater than 0% supports the business case by indicating that there is a net reduction in total expenses over the design life of the infrastructure. In contrast, an $I\&IEx$ saving ratio less than 0% does not support the business case for borrowing.

It is instructive to explore the impact of borrowing versus no borrowing management strategies over a broader range of two policy levers: 1) allowable fee-hike, and 2) preferred network rehabilitation rates. These policy levers are varied in a manner analogous to Section 4.7.1, over the same interest rate spread values of 0, 1.5, and 3% per annum. Maximum debt capacity (Q) is set at of 12.5% of utility's annual revenue, as indicated in Table 4.4.

Figure 4.5a to Figure 4.5c present the contours of $I\&IEx$ saving ratio over the benchmarking period, with 0, 1.5 and 3% per annum interest rate spread, respectively. These contours are the mean BPI values arising from the simulations (3,969 runs) for the three utilities. For comparative purposes, utilities X, Y and Z with a 7% allowable fee-hike rate and a 1.3% preferred network rehabilitation rate are illustrated using white dots on Figure 4.5a to Figure 4.5c. The results of different interest rates spread indicate that the three utilities, as depicted with white dots on Figure 4.5a to Figure 4.5c, operate on the green region

with an $I\&IEx$ saving ratio value in the range of 30 to 50%. This indicate that the borrowing management strategy with a 12.5% debt capacity can enable the three utilities saving more on $I\&I$ expenditures, with the unique allowable fee-hike of 7% per annum, and 1.3% preferred network rehabilitation rate per annum.

There is a clear trend where issuing debt ranges from spread of 0% to 3% per annum causes more interest expenditures. As the interest rate spread increases, interest expenditures also increase causing the utility to spend a greater proportion of income on servicing debt. This prevents the utility from rehabilitating the ICG 5 pipes quickly, and then slightly increase in the value of infrastructure condition efficiency BPI (i.e., length of ICG 5 pipes per capita), with a resulting increase in $I\&I$ flows. Figure 4.5a to Figure 4.5c show as long as the $I\&IEx$ saving ratio remains above 0% contour line, interest expenditures remain less than savings on $I\&I$ expenditures. In summary, issuing debt is a premier management strategy as long as the combinations of allowable fee-hike and preferred rehabilitation rates remain outside the 0% contour line, as shown in Figure 4.5a to Figure 4.5c.

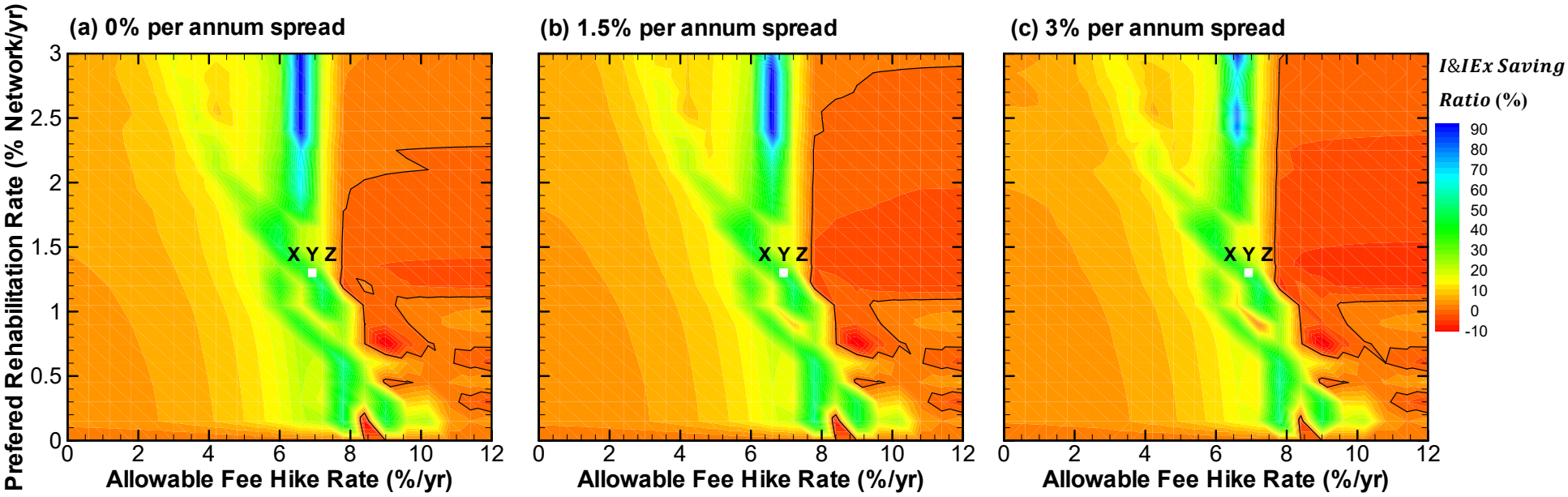


Figure 4.5: Impact of allowable fee hike and preferred rehabilitation rates on ***I&IEx*** Saving Ratio

4.8 Conclusions

Based on this study, the following conclusions can be drawn:

1- An advanced system dynamics model is developed to forecast the future behavior of wastewater collection networks.
2- The output of the advanced system dynamics model is then used to demonstrate the first known application of the entire benchmarking performance indicators for wastewater collection networks developed in Chapter 2.
3- An implementation framework for asset management strategy of wastewater collection networks is developed comprised of three decision-making layers: 1) visions & values, 2) function (i.e., advanced SD model), and 3) performance (i.e., BPI's).
4- Benchmarking results indicate that all three utilities can sustainably meet the strategic targets using the controlling policy lever over the benchmarking period.
5- The "optimal" combinations of allowable fee-hike and preferred rehabilitation rates along with a borrowing management strategy (i.e., issuing debt) will allow utilities to accelerate capital works and sustainably meet their strategic targets over the life cycle of assets.
6- Borrowing management strategy can be a practical and long-term solution for utilities to sustainably operate and maintain their assets using the combinations of allowable fee-hike and preferred rehabilitation rates that lead to a positive value of $I\&IEx$ saving ratio.

Chapter 5
Integrated Asset Management of Water Distribution and Wastewater Collection Networks

5.1 Introduction

In an urban water system, the water distribution network delivers potable water to the point of consumption, and the wastewater collection network carries sewage to a treatment plant (Grigg 2012). Water distribution and wastewater collection systems are often placed in the same construction trench and thus adjacent to each other. This means that deterioration in one system can impact the infrastructure, socio-political and financial aspects of the other system. For example, the amount of wastewater generated depends upon the water consumed, and the design flows for sewage systems are estimated as a function of water demand, and a deteriorated water main leakage can be a significant source of infiltration to a nearby sewer. Besides infiltration, the leaking water can also result in movement of soil particles around a sewer, resulting in loss of support and consequent damage to the sewer pipes. Exfiltration from a wastewater pipe can contaminate ground water which might be a source of supply for the water distribution system. Grigg (2009) indicates that the concepts of integration of water and wastewater infrastructure management systems have been under developed since 1917; however, Katko et al. (2010) suggest that the concepts of integrating water and wastewater infrastructure are familiar, but the idea as a whole has not been fully embraced. Many studies, including, but not limited to, Rehan et al. (2011; 2013; 2014a; 2014b; 2015) along with (Baah et al. 2015; Duchesne et al. 2013; Elsawah, Bakry, and Moselhi 2016; Ganjidoost, Younis, and Knight 2015; Hawari et al. 2016; Mashford et al. 2010; Park, Ting, and Jeong 2015; Scheidegger et al. 2011; Syachrani, Jeong, and Chung 2011; Tran, Marlow, and May 2010) have developed distinct and separate water distribution or wastewater collection systems asset management models. In these models no feedback loop and interaction exist that can investigate the impact of each system on the others behavior and long-term decision making. This study develops a novel integrated asset management model for water distribution and wastewater collection systems.

The following sections start with a detailed literature of water and wastewater asset management models then develops the first known integrated system dynamics (SD) asset management model for water distribution and wastewater collection systems that has feedback loops and interconnections. This is done through the development of causal loop diagrams. The integrated SD asset management model is

validated and implemented using data from one utility in Southern Ontario, Canada to explore the impact of interconnections and feedback loops in an integrated approach. Detailed discussions of model validation and implementation are provided in in Sections 5.5 and 5.6, respectively. The SD model is then used to investigate the significance of the interconnections and feedback loops on water and wastewater asset management decision making. Figure 5.1 presents a graphical summary of the research tasks performed to develop novel integrated asset management model for water distribution and wastewater collection systems.

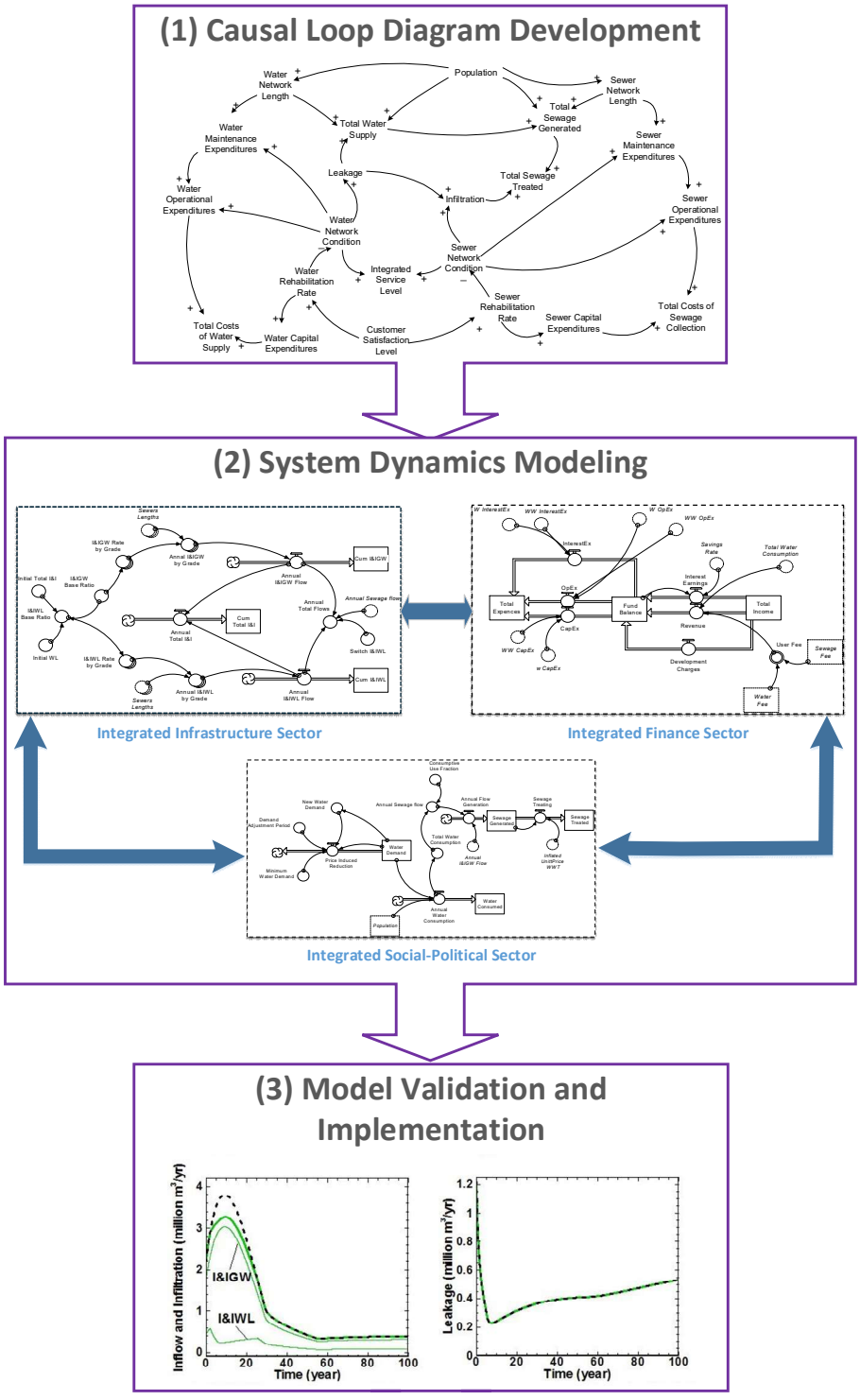


Figure 5.1: Framework of the integrated asset management of water distribution and wastewater collection networks

5.2 Literature Review

This section provides a detailed review of asset management models, decision support systems (DSS), and system dynamics models for water distribution and wastewater collection networks. These models are investigated with respect to four questions, noted in Section 5.2.1. The evaluation of these models indicates that the current asset management models, DSS and SD models are applied either to water distribution or wastewater collection systems. The dynamic behavior of water distribution and wastewater collection systems has not been studied in an integrated approach.

5.2.1 Asset Management Models for Water Distribution and Wastewater Collection Systems

Fourteen representative published asset management models for water distribution and wastewater collection networks, noted in Table 5.1, have been evaluated with respect to the following four questions:

A. Does the model integrate infrastructure, socio-political and finance sectors?
B. Is it a water distribution asset management model?
C. Is it a wastewater collection asset management model?
D. Does it integrate water distribution and wastewater collection asset management models?

Table 5.1 shows many distinct and separate water distribution and wastewater collection network models have been developed but none are integrated models that take into consideration feedback loops and interconnections between water distribution and wastewater collection networks (Question D).

Table 5.1: Selected water distribution and wastewater collection asset management models

Author (s)	Characteristics	Limitations			
		A	B	C	D
Kleiner et al. (1998)	Dynamic programming combined with partial and (sometimes) implicit enumeration schemes for identification of an optimal rehabilitation strategy that minimized the total costs of rehabilitation and all maintenance over a planning horizon of a water distribution network. Structural deterioration was modeled with age of pipes as the only explanatory variable.	N	Y	N	N
Fenner and	A model for the rehabilitation of non-critical sewers using GIS	N	N	Y	N

Sweeting (1999)	techniques. This is identification of economically optimal group of pipe lengths along with priority order for rehabilitation strategies.				
Lalonde and Bergeron (2003)	Using reliability theory and multi-criteria decision support tools for modeling asset failure risk in three levels i.e., segment, network and strategic level analysis. Only the segment level problem could be resolved on the basis of bi-criteria methods. For the strategic management interdependencies between various infrastructure networks such as water, sewers, and roads should be considered.	N	Y	Y	N
Giustolisi et al. (2006)	Evolutionary polynomial regression method to predict the burst rates of water mains. And to compare the reduction in burst rates after pipes' replacement against the cost of replacement. The results utilized for assigning replacement priorities to individual water mains. The study did not take rehabilitation options into account.	N	Y	N	N
Dandy and Engelhardt (2006)	Multi-objective genetic algorithm approach was adopted by to develop trade-off curves between economic cost and reliability for replacement schedules of water pipes. The model can be used either for identifying a minimum economic cost to maintain certain performance standard or alternatively for a given budgetary constraint the maximum achievable reliability measure can be identified.	N	Y	N	N
Hong et al. (2006)	Optimum scheduling of water mains replacement and rehabilitation with the objective to minimize the expected annual average costs.	N	Y	N	N
Tabesh et al. (2009)	Development of a multivariate regression approach to enable comparison of Artificial Neural Network and neuro-fuzzy systems for pipe failure rate. The results found that the artificial neural network model is more realistic and accurate in the prediction of pipe failure rates and evaluation of mechanical reliability in water distribution networks.	N	Y	N	N
Ward and Savic (2012)	A multi-objective genetic algorithm optimization model for the optimal specification of sewer rehabilitation. The methodology includes three objectives: (1) maximizes structural condition, (2) minimizes	N	N	Y	N

	construction cost, and (3) minimizes risk of critical asset failure.				
Younis and Knight (2014)	A multi-perspective asset management plan for wastewater collection networks. The framework considered four strategic perspectives-socio-political, financial, operational/technical, and regulatory. It is a useful framework for effective strategic asset management plans of wastewater collection systems.	N	N	Y	N
Rehan et al. (2011)	Proposes an interconnected municipal water and wastewater asset management framework using a system dynamic model. This management framework assists water utilities in whole life-cycle cost analysis. The model demonstrates complex interconnections and feedback loops between the physical infrastructure, financial and socio-political sectors. System dynamics modeling is applied for water and wastewater network pipeline asset management. Their work was the first known application of system dynamics to water and wastewater infrastructure asset management.	Y	N	N	N
Rehan et al. (2013)	Proposes a financially sustainable management strategies model for urban water distribution infrastructure using system dynamics. They presented the first known causal loop diagram to lay out the interrelationships among system components of an urban water distribution network. This system dynamics model demonstrates complex interactions and feedback loops among physical, financial, and socio-political sectors, and is the first know decision support tool to quantitatively simulate the influence of interrelationships and feedback loops in water distribution infrastructure management.	Y	Y	N	N
Rehan et al. (2014a)	Presents a financially sustainable management strategies system-dynamics model for urban wastewater collection infrastructure. This system dynamics model identifies complex interactions and feedback loops among physical, financial, and socio-political sectors, and is the first know decision support tool to quantitatively simulate the influence of interrelationships and feedback loops in wastewater collection	Y	N	Y	N

	infrastructure management. The model includes a set of policy levers which allows utility managers to monitor the impact of financing and rehabilitation strategies on system performance in terms of financial and service level metrics.				
Roshani and Filion (2013)	An event-based approach to optimize the timing of water main pipe replacement, duplication, lining, new pipe installation with asset management strategies (infrastructure adjacency and quantity discounts applied to the installed pipe)	N	Y	N	N
Scholten et al. (2014)	Predicts the long-term performance of rehabilitation strategies. The model uses multi-criteria decision analysis and scenario planning to evaluate18 strategic rehabilitation alternatives under future uncertainty with three objectives (low costs, high reliability, and high intergenerational equity).	N	Y	N	N

Note: the answers to the above questions are responded with Yes (Y) or No (N).

5.2.2 Decision Support Systems for Water Distribution and Wastewater Collection Asset Management

Decision support system (DSS) refers to the use of computers to store, analyze, and display information that is used to support decision-making. Grigg (2012) defines DSS as: “an advisory system for management, usually computer-based, that utilizes databases, models, and communication/dialog systems to provide decision makers with management information”. This definition is used to distinguish DSS from general asset management models. Eight representative decision support systems are evaluated for water distribution and wastewater collection asset management (Table 5.2) with respect to Questions A to D as listed in Section 5.2.1. A review of the DSS shows that none of the current DSS have addressed the Questions A and D.

Table 5.2: Selected water and wastewater infrastructure DSS

DSS	Author (s)	Characteristics	Limitations			
			A	B	C	D
KANEW	Deb et al. (1998)	This model is based upon the concept of survival function which is a statistical prediction of useful life of a group of pipes belonging to the same class (e.g. age, material, and diameter). The model does not predict specific water mains which should be rehabilitated or replaced each year	N	Y	N	N
UtilNets	Hadzilacos et al. (2000)	A DSS for rehabilitation planning and optimization of the maintenance of underground water distribution pipe networks which facilitates rehabilitation of critical water mains.	N	Y	N	N
Pipeline Asset & Risk Management System (PARMS) Planning	Burn et al. (2003)	It optimizes management and operational strategies for both short and long-term repair and replacement of water pipelines.	N	Y	N	N
PARMS-PRIORITY	Moglia et al. (2006)	As a complement to the PARM-PLANNING model. The system is comprised of the following modules: risk calculation, failure predictions, cost assessment, scenario evaluation, and data exploration	N	Y	N	N

CARE-W (Computer Aided Rehabilitation of Water Networks)	Saegrov (2005)	A framework for water network rehabilitation. The system consists of modules for assessment of performance indicators, prediction of pipe failures, and calculation of water supply reliability	N	Y	N	N
CARE-S (Computer Aided Rehabilitation of Sewer Networks)	Cardoso et al. (2006)	A comprehensive DSS that combines several tools relevant to wastewater infrastructure management into a single platform. These tools allow for: assessment and forecast of performance indicators, socio-economic and environmental risk definition, assessment and prediction of structural, hydraulic and environmental conditions of sewer networks, and optimization of rehabilitation investment.	N	N	Y	N
REHAB (Integrated planning of rehabilitation strategies of urban infrastructure systems	Kleidorfer et al. (2013)	A strategic planning tool for designing rehabilitation strategies by incorporating climate change impacts, city development and sewer pipe deterioration.	N	N	Y	N
AWARE-P	AWARE-P (2016)	A direct successor of CARE-W and CARE-S efforts that articulates the three types of decisional levels (strategic, tactical and operational) and the main knowledge competences involved (engineering,	N	Y	Y	N

	management and information), along the three principal assessment dimensions: performance, risk and cost.
RIVA, Hansen, InfraModex, MIMS, CityWorks, Synergen, Infrastructure 2000, IBM Maximo, and Harfan	Majority of these commercial software packages focus on operational management and have a little or no functionality to support long-term renewal planning decisions (Halfawy et al., 2006). None of them are water and wastewater asset specific management tools rather; they can be categorized as corporate asset management tools.

Note: the answers to the above questions are responded with Yes (Y) or No (N).

5.2.3 Application of System Dynamics to Water Distribution and Wastewater Collection Infrastructures Management

System Dynamics (SD) is a feedback-based object-oriented modeling paradigm developed by Forrester (1958) to model complex systems. SD modeling has been used by several researches with the domain of management, water resources planning and management, construction management, economics, urban policy, etc. A detailed discussion on SD applications can be found in Richmond et al. (2001), Sterman (2000; 2001), Ford (1999; 2000), and Coyle (1996). A summary of the application of system dynamics to water distribution and wastewater collection systems is provided below.

Rehan et al. (2011) proposed an interconnected municipal water and wastewater asset management framework using a system dynamic model. This management framework assists water utilities in the whole life-cycle cost analysis. The model demonstrates complex interconnections and feedback loops between the physical infrastructure, financial and socio-political sectors. System dynamics modeling is applied for water and wastewater network pipeline asset management. Their work is the first known application of system dynamics to water and wastewater infrastructure asset management.

Rehan et al. (2013) developed a financially sustainable management strategies model for urban water distribution infrastructure using system dynamics. They presented the first known causal loop diagram to lay out the interrelationships among system components of an urban water distribution network. This system dynamics model demonstrates complex interactions and feedback loops among physical, financial, and socio-political sectors, and is the first know decision support tool to quantitatively simulate the influence of interrelationships and feedback loops in water distribution infrastructure management. In a separate study (Rehan et al. 2015), they demonstrated the implementation of their water distribution system dynamics model to a medium-sized water utility in Southern Ontario.

Qi and Chang (2011) proposed a SD modeling for municipal water demand estimation in an urban region under uncertain economic impacts. They developed a new system dynamics model to reflect the intrinsic relationship between water demand and macroeconomic environment for long-term municipal water demand forecasts in a fast growing urban region.

Osman and Hassan (2012) proposed a SD modeling to represent the interconnections among infrastructure assets, system operators, users and politicians. The model focuses on how the budgets allocation impact on user fees, lever of service, and user satisfaction.

Rehan et al. (2014a) developed a financially sustainable management strategies system dynamics model for urban wastewater collection infrastructure. This system dynamics model identifies complex interactions and feedback loops among physical, financial, and socio sectors, and is the first know decision support tool to quantitatively simulate the influence of interrelationships and feedback loops in wastewater collection infrastructure management. The model includes a set of policy levers which allows utility managers to monitor the impact of financing and rehabilitation strategies on system performance in terms of financial and service level metrics.

Rehan et al. (2014b) demonstrated the implementation of a system dynamics model developed by Rehan et al. (2014a) for urban wastewater collection infrastructure. This model can assist utility managers to ensure financial sustainability while maintaining customer expectations for service performance. They developed a case study using data form a medium-sized utility in southern Ontario, Canada. The model explores the impacts of alternative financially sustainable management strategies: (1) a 'zero fund balance' with no borrowing versus (2) issuing debt to accelerate capital working. The simulation results indicate that a financing strategy with borrowing can minimize the total life-cycle cost while maximizing the service level of the network.

5.3 Causal Loop Diagram Development

In system dynamics, the qualitative relationships among the various parameters influencing a system are represented through a Causal Loop Diagram (CLD) or Influence Diagram. The positive or negative influence of a variable is given by the loop polarity through a plus (+) or minus (-) sign, respectively (Sterman 2000). A positive link indicates that an increase (decrease) in one parameter causes an increase (decrease) in other parameters. Similarly, a negative link indicates that the dependent variable is inversely proportional to the cause, so that an increase (decrease) in one variable will result in a decrease (increase) of the dependent variable(s). A CLD for the integrated asset management of water distribution and wastewater collection networks is developed to lay out the connection points and identify the interacting feedback loops that exist among infrastructure, finance, and socio-political sectors.

The volume of total sewage treated depends upon the total sewage generated and infiltration to the sewer pipes (Figure 5.2). Deterioration in water mains can increase the breakage rate and consequently increase leakage in water mains. A water main leakage could be a significant source of infiltration to a nearby sewer. Besides infiltration, the leaking water might cause movement of soil particles around a

sewer, resulting in loss of support and consequent damage to the sewer pipes. Exfiltration from a wastewater pipe can contaminate ground water which might be a source of supply for the water distribution system. Therefore, an increase in water main leakage causes an increase in sewer infiltration. Increasing water leakage will enforce the water utility to supply more water to customers. Increased sewer infiltration means more sewage generated and ultimately leads to higher volume of sewage treated (Figure 5.2).

Integrated service level measures the level of service that a water utility delivers to its customers. The integrated service level depends upon the water and sewer networks condition. The network condition is measured quantitatively, where an increase in network condition means pipes are deteriorating and a decrease means pipes are moving toward the best condition (i.e. new pipes). Therefore, leakage increases as the water main network condition increases. Increased leakage causes more sewer infiltration, and as infiltration rate increases, sewers deteriorate faster (or network condition increases).

Reinforcing loop R1 indicates that an increase (or decrease) in water network condition leads to increase (or decrease) in the integrated service level (Figure 5.2, R1). Similarly, reinforcing loop R2 shows that an increase (or decrease) in wastewater network condition leads to increase (or decrease) in the integrated service level (Figure 5.2, R2).

Reinforcing loop R3 shows that an increase in the integrated level of service increases customers' willingness (acceptance of fee hike) to pay more fees (fee hike). As user fee increases, revenue increases as well, and increased revenue causes increase in the integrated service level (Figure 5.2, R3).

Balancing loop B1 shows that as the user fee increases, the dollar's value that customers pay (user bill) increases as well. This increase leads to a decrease in the satisfaction level. Customer satisfaction is measured quantitatively to determine the satisfactory level of services (on a scale of 0 to 100) delivered to them. As the customer satisfaction level decreases, the willingness to pay decreases, and ultimately user fee decreases as well (Figure 5.2, B1).

Balancing loop B2 shows that an increase in total costs of water supply decreases available cash for rehabilitation water distribution network. Shortfall in available cash for rehabilitation (capital works) increases the water network condition which causes increase in the integrated service level (Figure 5.2, B2).

Balancing loop B3 show that an increase in total costs of sewage decreases available cash for rehabilitation of wastewater collection network. Shortfall in available cash for rehabilitation (capital works) causes in increase in the integrated service level (Figure 5.2, B3).

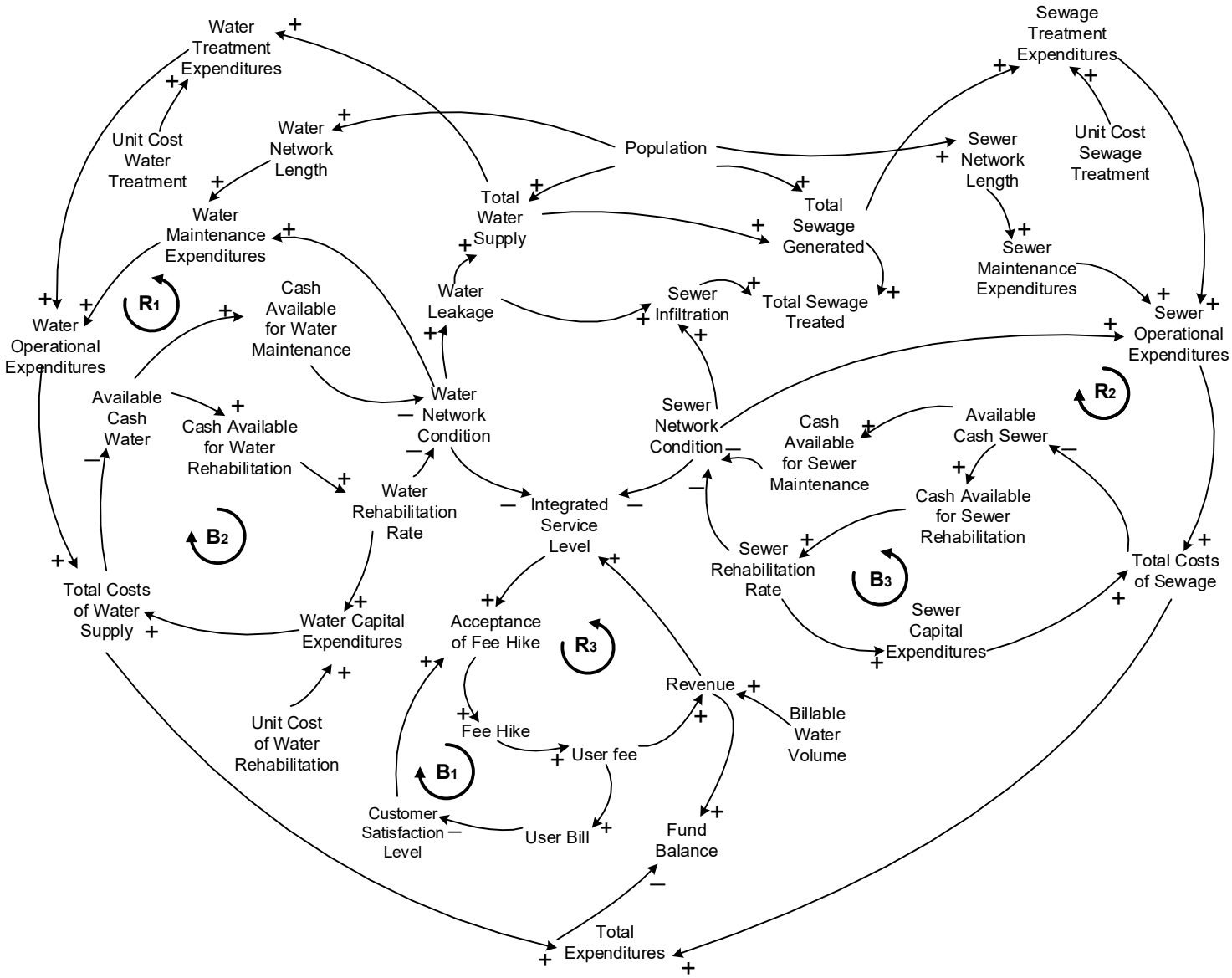


Figure 5.2: Causal Loop Diagram for the Integrated Asset Management of Water Distribution and Wastewater Collection Networks

5.4 System Dynamics Model Development

System dynamics is applied to develop an integrated asset management system for water distribution and wastewater collection networks. The SD demonstration model is used to understand the complex behavior of water and wastewater infrastructure systems, and to show the impact of complex interconnections and feedback loops on management decisions. SD is used for modeling the complexity of integrated water and wastewater systems. If a system is of 4^{th} or greater order then it can be referred to as a high order system where the order refers to the number of state variables (stocks) (Forrester 1969). In the proposed model, more than four stocks are included within the boundaries of this study model. Examples include the stocks representing inventories of water and wastewater pipes in different condition grades, water demand, user fee, fund balance, etc. Therefore, the study addresses a complex problem which can be modeled using SD. Several commercial software packages are available for SD modeling (i.e., Stella, Vensim and Powersim). The proposed model is implemented using research version 9.1.4 of Stella® software (Richmond, Peterson, and Soderquist 2001) due to its useful features (such as a library of built-in functions, capability of using graphical functions, and sensitivity analysis) and ability to extend current developed Rehan et al. (2013; 2014a) SD models. The basic building blocks of system dynamics modeling are: stocks, flows, converters, and connectors, as shown in Figure 5.3.

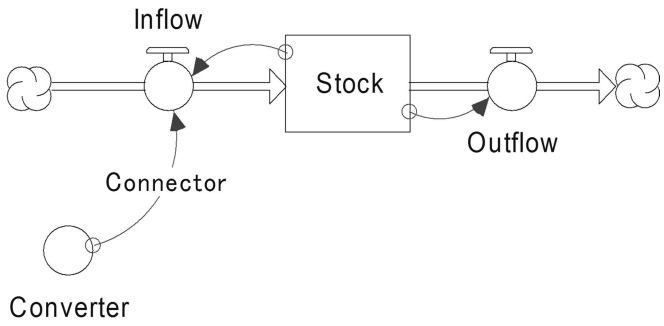


Figure 5.3: Building blocks of System Dynamics model

Stocks represent accumulations both physical and non-physical. For example, inventory of water and wastewater pipes and a customer's level of satisfaction. Stocks represent the 'traces' left by activities. Flows represent activities or actions. They transport quantities and can change instantaneously. The relationship between stocks and flows represented as follow:

$$Stock(t) = \int [Inflow(t) - Outflow(t)]dt + Stock(t_0) \qquad (5.1)$$

Connectors carry information to serve as inputs for decisions or actions. Converters are containers for performing algebra; they house graphical and built-in functions.

The system dynamics model for integrated asset management of water distribution and wastewater collection networks is comprised of three sectors: (1) integrated water and wastewater infrastructure, (2) integrated finance, and (3) integrated socio-political. A description of these sectors is presented as follow.

5.4.1 Integrated Water and Wastewater Infrastructure Sector

This sector represents the asset inventory of wastewater and water mains. The physical condition of the water main is classified based on the age distribution (i.e., in 25-year increments). The physical condition of the wastewater main is categorized into five stocks (variables) based on the internal condition of the pipes using the UK's Water Research Centre rating system proposed in the fourth edition of the Sewerage Rehabilitation Manual (WRc, 2001). The age-based deterioration models used by Rehan et al. (2013; 2014a) and used in Chapters 2, 3 and 4 are adapted herein to measure the average duration that a water or wastewater pipe continues to stay in each stock.

Rehan et al. (2014a) measured extraneous flow volumes of inflow and infiltration ($I\&I$) based on the internal condition grade (ICG) of pipes. This means as pipes move to the worst condition, the infiltration rate increases. There is a feedback loop between physical condition of water and wastewater networks. Deterioration of water mains increases the rate of leakage which can be a significant source of infiltration to a nearby sewer pipe. Therefore, this study calculates total volume of $I\&I$ based on two sources: 1) ground water (GW), and 2) water leakage (Wl).

Convertor *I&IGW Base Ratio* contains user specified value (from 0 to 1) to determine the ratio of *I&IGW* to *Total I&I*, as shown in Figure 5.4. Subsequently, the model calculates the ratio of *I&IWl* to *Total I&I*. The convertor *I&IWl Base Ratio* is determined using Equation 5.2.

$$I\&IWl\ Base\ Ratio\ = (1 - I\&IGW\ Base\ Ratio) \times (\frac{Initial\ Total\ I\&I}{Initial\ Wl}) \qquad (5.2)$$

where, *Wl* is water leakage; *GW* is ground water; *Initial TotalI&I* is the initial volume of total inflow and infiltration specified by user; *InitialWl* is the initial volume of annual water leakage specified by user.

For each ICG, convertor *I&IGW Rate by Grade* contains user specified values for annual ground water infiltration volume per unit length of pipes (Figure 5.4). Similarly, for each ICG, convertor *I&IWl Rate by Grade* contains user specified values for annual water leakage infiltration volume per unit length of pipes (Figure 5.4). These values are multiplied by the corresponding lengths of pipes in each ICG to determine annual infiltration volumes from ground water ($I\&IGW$) and water leakage ($I\&IWl$).

The $TotalI\&I$ volume is determined using Equation 5.3. Sewage flow is combined with $TotalI\&I$ volume to determine total annual flow volume (Equation 5.4).

$$Total\ I\&I\ =\ I\&IGW\ +\ I\&IWL \qquad (5.3)$$

where, GW represents ground water and Wl represents water leakage.

$$Annual\ Total\ Flow = Annual\ Sewage\ Flow + Annual\ Total\ I\&I\ Flow \qquad (5.4)$$

If the condition of water mains improves, as a result the $Annual\ Wl$ volume reduces. However, if the internal condition grade (ICG 1 to 5) of sewer pipes increases (i.e., moving to ICG 5), even the $Annual\ Wl$ volume reduces, but still the $Annual\ I\&IWl$ volume increases which cannot be happened in real practice. The model then controls the volume of $Annual\ Wl$ generated based on the water mains condition, and the volume of $Annual\ I\&IWl$ contributed to the $Total\ I\&I$ volume which depend on the internal condition grade of sewer pipes (Equation 5.5).

$$IF\ \sum_{i=1}^{5} Annual\ I\&IWl_i > Annual\ Wl\ THEN\ Annual\ Wl\ ELSE\ \sum_{i=1}^{5} Annual\ I\&IWl_i \qquad (5.5)$$

where, i represents internal condition grade from 0 to 5.

The utility's infrastructure policy levers, as illustrated in Figure 5.5, are established in this sector: 1) network preferred rehabilitation rate per year, 2) maximum acceptable fraction of highly deteriorated water mains as percentage of the total network length; 3) desired elimination period (year) of highly deteriorated water mains; 4) maximum acceptable fraction of ICG 5 pipes for wastewater network as percentage of the total network length; 5) desired elimination period (year) of ICG 5 pipes; and 6) $I\&IGW$ base ratio.

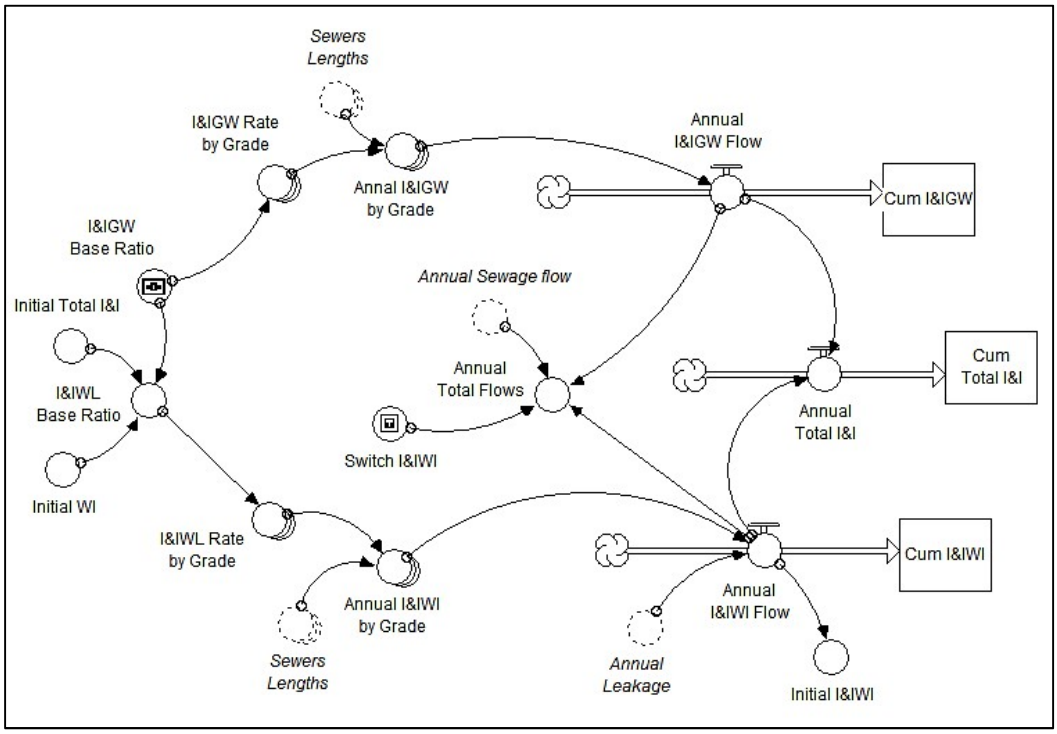


Figure 5.4: ***I&I*** calculations for the integrated physical sector in Stella®

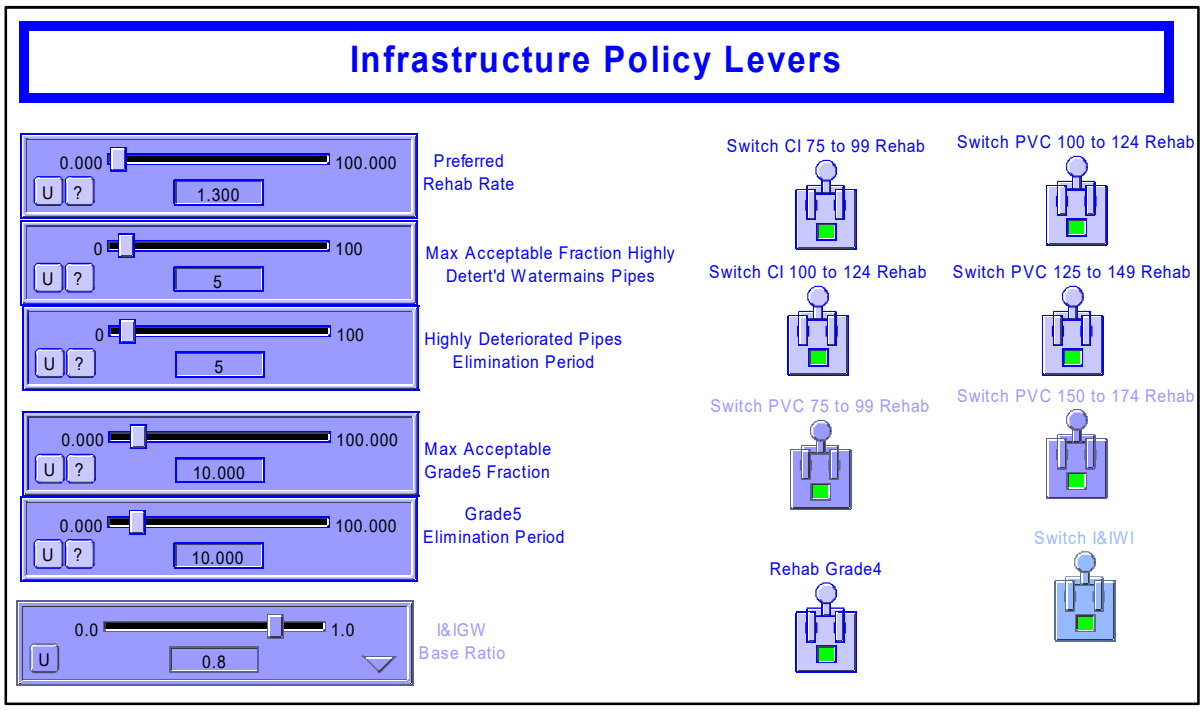


Figure 5.5: Integrated infrastructure policy levers in in Stella®

5.4.2 Integrated Finance Sector

The integrated finance sector describes the integrated water and wastewater networks' financial situations with special emphasis on utility's total income (i.e., revenue, interest earning and development charges), total expenses (i.e., operational, capital and interest expenditures), fund balance, debt, cash reserve and user fee, as illustrated in Figure 5.6. Revenue is the utility's income that is calculated based upon user fee, total water consumption, and total generated sewage. Fund balance is the difference between total income and total expenditures of the integrated network in dollars value, and user fee contains the unit cost of water and sewage ($\$/m^3$) that utility charges to customers to cover the expenses of water and sewage services.

The integrated finance sector accumulates incomes received from each water and wastewater utility into one account as a total income. Thus, the financial capacity of utilities to pay for capital, operational and interest expenditures increases, because of the integration of the utilities financial resources.

The utility's finance policy levers are established in this sector, as illustrated in Figure 5.7: 1) water (W) and wastewater (WW) allowable fee-hike rates, 2) desired reserve fraction for W and WW as percentage of network's value; 3) initial unit costs of W, WW, water treatment and wastewater treatment; 4) maximum debt capacity as percentage of utility's annual revenue. In addition, Figure 5.7 shows borrowing rate, saving rate, and inflation rates for the maintenance and construction costs of the water and wastewater networks.

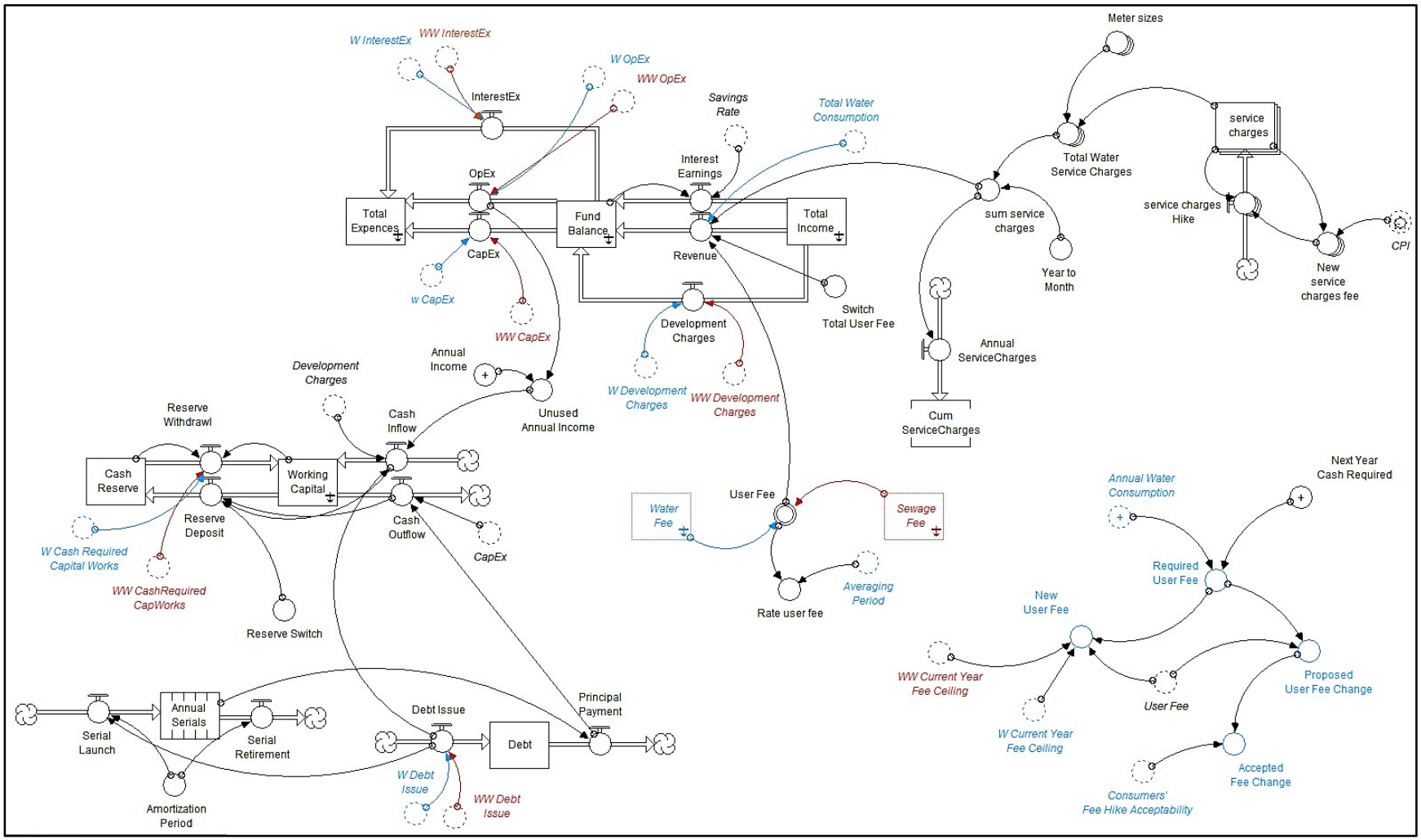


Figure 5.6: Integrated finance sector in Stella®

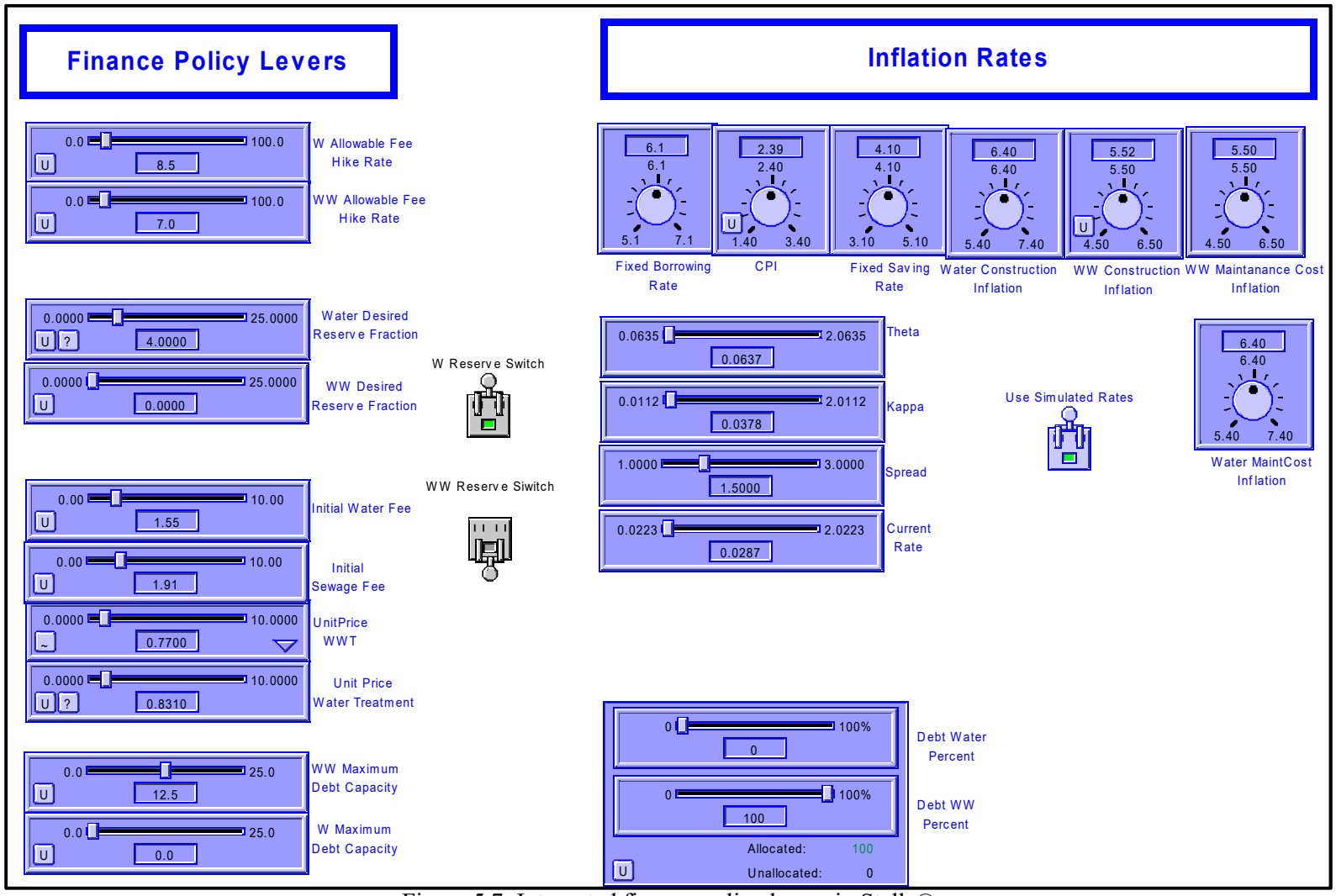


Figure 5.7: Integrated finance policy levers in Stella®

5.4.3 Integrated Socio-Political Sector

This sector presents the behavior of customers in response to user fee oscillations in water demand and integrated service level, as depicted in Figure 5.8.

Convertor *User Fee Hike Acceptability Level* contains user specified values to determine the customers' level of acceptability to user fee hike as a function of fraction of highly deteriorated integrated water (75+ years) and wastewater (ICG 5) pipes.

The volume of sewage generated (convertor *Sewage Flow*) by different classes of customers is subtraction of *Total Water Consumption* from *Consumptive Use Fraction* in the integrated customer sector. Convertor *Consumptive Use Fraction* represents the percentage of water received by customers that is not returned as sewage to the wastewater collection network. For instance, water used in watering lawns and evaporated from pools. Convertor *Total Water Consumption* is the product of the average per capita water demand and population served by the utility (residential consumption), and the average per service water demand and number of services served by the utility (commercial, industrial and institutional).

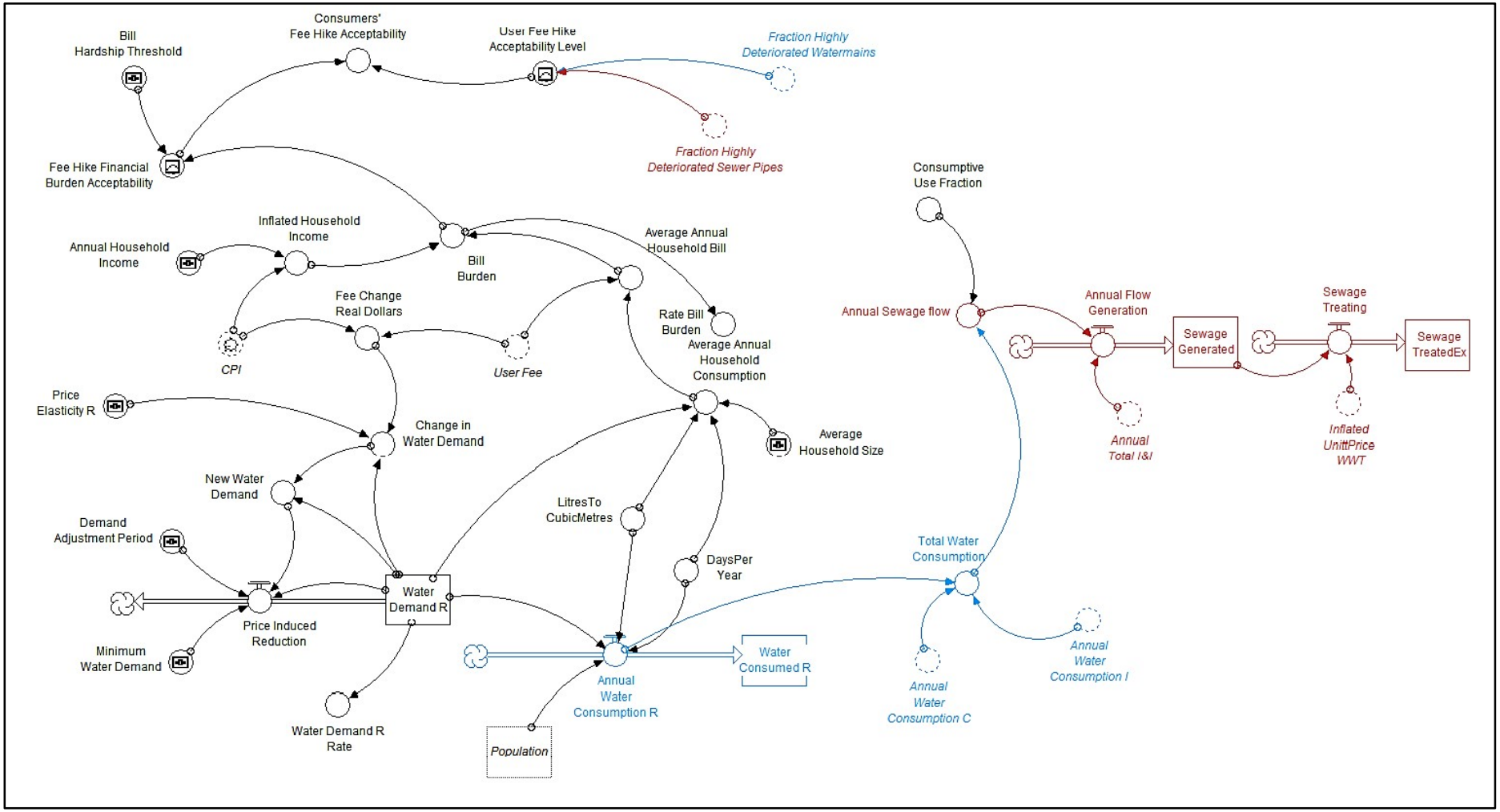


Figure 5.8: Integrated socio-political sector in Stella®

5.4.4 Data Requirements for Integrated System Dynamics Model

The required data to populate the integrated water and wastewater system dynamics model are itemized in Table 5.3.

Table 5.3**:** Data requirements for the integrated water and wastewater system dynamics modeling

Sector	Data	Unit
Integrated Water and Wastewater Infrastructure	Initial total length of a given pipe material as a function of its age.	Kilometer $[km]$ or meter $[m]$
	Network condition (condition assessment history)	Water mains $[year]$, sewer pipes $[ICG]$
	Inflow and infiltration $(I\&I)$ and water leakage volumes (for the purpose of the deterioration modeling)	$[m^3], [L] or\ [ML]$ $L = litre$ $ML = mega\ litre$
	inventory of water meters as specified by the diameter in millimeter	$[mm]$
	Current and preferred rehabilitation rate (percent of the network per year)	$[\%/year]$
	Maximum acceptable fraction of deteriorated pipes over design life $(\mathbb{D})$ for water mains and ICG 5 for wastewater pipes	$[\%]$
	Desired elimination period for deteriorated water and wastewater pipes	$[year]$
Integrated Finance	Unit cost of water, water treatment, wastewater, and wastewater treatments	$[\$/m^3]$
	Current fund balance	$[\$]$
	Current and past history of capital and operational expenditures	$[\$/year]$

	Unit charge of potable water services and wastewater services per service connection.	$[\$/year]$
	Approved fee hike rate	$[\%/year]$
	Development charges	$[\$/year]$
	Unit costs of rehabilitation/replacement, operation & maintenance	$[\$/m]$
	Inflation, borrowing and saving rates	[%]
	Maximum debt capacity per year as percentage of annual revenue	[%]
	Desired reserve fraction as percent of total network value	[%]
Integrated Socio-Political	Population (number of different classes of customers such as residential, commercial and institutional)	$[-]$
	Population growth	$[\%/year]$
	Usage history (i.e. water demand) *Litre* (l) *per capita* (c) *per year*	$[lpcd]$
	Minimum water demand	$[lpcd]$
	Price elasticity of water demand	$[-]$
	Annual supplied water	$[m^3]$
	Annual treated wastewater	$[m^3]$
	Annual average household income	$[\$/year]$
	Average household size	$[-]$
	Service coverage area	$[m^2]$

5.5 Integrated System Dynamics Model Validation

Three test methods adopted from Sterman (2000), as described in Table 5.4, are used to validate the developed integrated SD model:

1) Structure assessment test is conducted to check the level of aggregation for consistency with knowledge of the real system relevant to the purpose. Partial model tests are conducted to check the rationality of individual decision rules. For this purpose, the level of aggregation for integrated water and wastewater models is tested by comparing the behavior of water and wastewater models individually compared to the integrated model. The results indicate that the aggregated water and wastewater SD models shows similar behavior as integrated SD model, as illustrated in Figure 5.9.
2) Extreme condition test is conducted to check for unlikely behavior of the system in face of extreme conditions. For this purpose, minimum and maximum values are assigned to various parameters.
3) Integration error test is carried out to ensure that the model results are not sensitive to the choice of time step. Thus, simulations are conducted by cutting the time step value in half and quarter and changes are assessed. It indicates no significant changes in the integrated SD modeling results.

Table 5.4: Test methods for the SD model validation-adopted from Sterman (2000)

	Test Method	**Description**	**Procedure**
1	Boundary adequacy	To assess whether the chosen model boundary is appropriate for the intended purpose	Constructing model boundary charts and presenting them to key experts and review of relevant literature to check if adding plausible structure and changing exogenous variables to endogenous affect the behavior of the proposed model
2	Dimensional consistency	To check the dimensionally consistency of each equation	The Stella® software has the capability to perform dimensional consistency check

3	Structure assessment	To check the level of aggregation for consistency with knowledge of the real system relevant to the purpose	Partial model tests should be conducted to check the rationality of individual decision rules. For example, the level of aggregation for integrated water and wastewater model can be tested by comparing the behavior of water and wastewater models individually to the integrated model
4	Parameter assessment	To ensure that the parameter values are consistent with relevant descriptive and numerical knowledge of the system and variable has a clear meaning	Parameters for which numerical data is available, statistical methods are employed to estimate the parameters. When numerical data is not available for some parameters, then those can be estimated judgmentally using information from interviews, workshops, and archival materials, etc.
5	Extreme condition or reality checks	To check for unlikely behavior of the system in face of extreme conditions	Assigning minimum and maximum values to various parameters
6	Integration error	To ensure that the model results are not sensitive to the choice of time step	Conducting simulations by cutting the time step values in half and test for changes
7	Behavior anomaly	To check if a change or deletion of a relationship has anomalous behavior result	Replacing equilibrium assumptions with disequilibrium structures
8	Sensitivity analysis	To check how model predictions respond when the uncertain parameters are varied over the feasible range of uncertainty	Numerical sensitivity: numerical changes Behavior sensitivity: modes of behavior changes Policy sensitivity: Policy implication changes

5.6 Demonstration of the Integrated Asset Management Model

A medium-sized city in Southern Ontario, Canada with 361 km of water mains and 341 km of sewer pipes which serves 120,000 customers is used to demonstrate the application of the integrated asset management system dynamics model for water distribution and wastewater collection networks. The objective is to discover the impact of interconnections and feedback loops that exist among the integrated infrastructure, finance and socio-political sectors. For this purpose under the same assumptions, variables and parameters, the simulation results of the integrated water and wastewater and the aggregated-separate water and wastewater models are compared over a 100-year life cycle. It should be noted that the aggregated-separate model means each water and wastewater SD models are simulated in isolation without any interaction, and then the results are aggregated to be comparable with the integrated water and wastewater model. The two models are compared using a borrowing management strategy for wastewater collection network and a capital reserving management strategy for water distribution network. Six policy levers, as presented in Table 5.5 control the system behavior to optimally manage the water and wastewater infrastructures over their life cycle. It should be noted that the $I\&IGW$ base ratio is assumed to be 0.8, as described in Section 5.4.1.

Table 5.5: Optimal policy levers for asset management of integrated/aggregated-separate SD models

	Optimal Policy Lever	Network	Value
1	Allowable Fee-Hike Rate (% per annum)	Water distribution	8.50
		Wastewater collection	7.0
2	Desired Cash Reserve (% of annual network value)	Water distribution	4
3	Allowable Debt Service (% of annual revenue)	Wastewater collection	12.5
4	Maximum Fraction of Highly Deteriorated Pipes (% of Network)	Water distribution	5
		Wastewater collection	10
5	Desired Elimination Period for Highly Deteriorated Pipes (year)	Water distribution	5
		Wastewater collection	10
6	Preferred Rehab Rate (% of Network per year)	Water & Wastewater	1.3

5.6.1 Simulation Results

The simulation results of the integrated water (W) and wastewater (WW) and aggregated-separate W&WW models are compared using a borrowing scenario (i.e., issuing debt) for wastewater collection and a capital reserving scenario for water distribution networks. The simulation results are depicted in Figure 5.9. It should be noted that the results of the integrated water and wastewater validation (Figure 5.9a and 5.9b) are demonstrated for the purpose of the system dynamics model validation (see Section 5.5). Partial model tests are conducted to check the rationality of individual decision rules. Each water distribution and wastewater collection sectors of the integrated water and wastewater model is simulated in isolation without having any interactions or feedback loops. The simulation results show similar behavior as the aggregated-separate water and wastewater, as shown in Figure 5.9a and 5.9b.

The six variables of a) user fee, b) user fee hike, c) cumulative cash reserve and cumulative debt, d) debt service ratio, e) annual inflow and infiltration ($I\&I$), and f) annual water leakage are compared over a 100-year planning horizon.

Figure 5.9a shows user fee for both integrated water and wastewater, and aggregated-separate water and wastewater models. The user fee starts with a value of $\$3.5/m^3$ for both models. It follows with some oscillations in the first 5 years, increases to 40 years, continues linearly to the end of the simulation to reach values of $\$6.6\ and\ \$6.4/m^3$ for integrated W&WW and aggregated-separate W&WW models, respectively (Figure 5b).

The oscillations in user fee are presented in terms of user fee hike which shows the rate of changes in user fee per year (Figure 5.9b). The results show that the maximum fee hike rate of 7.5% and 8.5% reached by the integrated W&WW and aggregated-separate W&WW models, respectively.

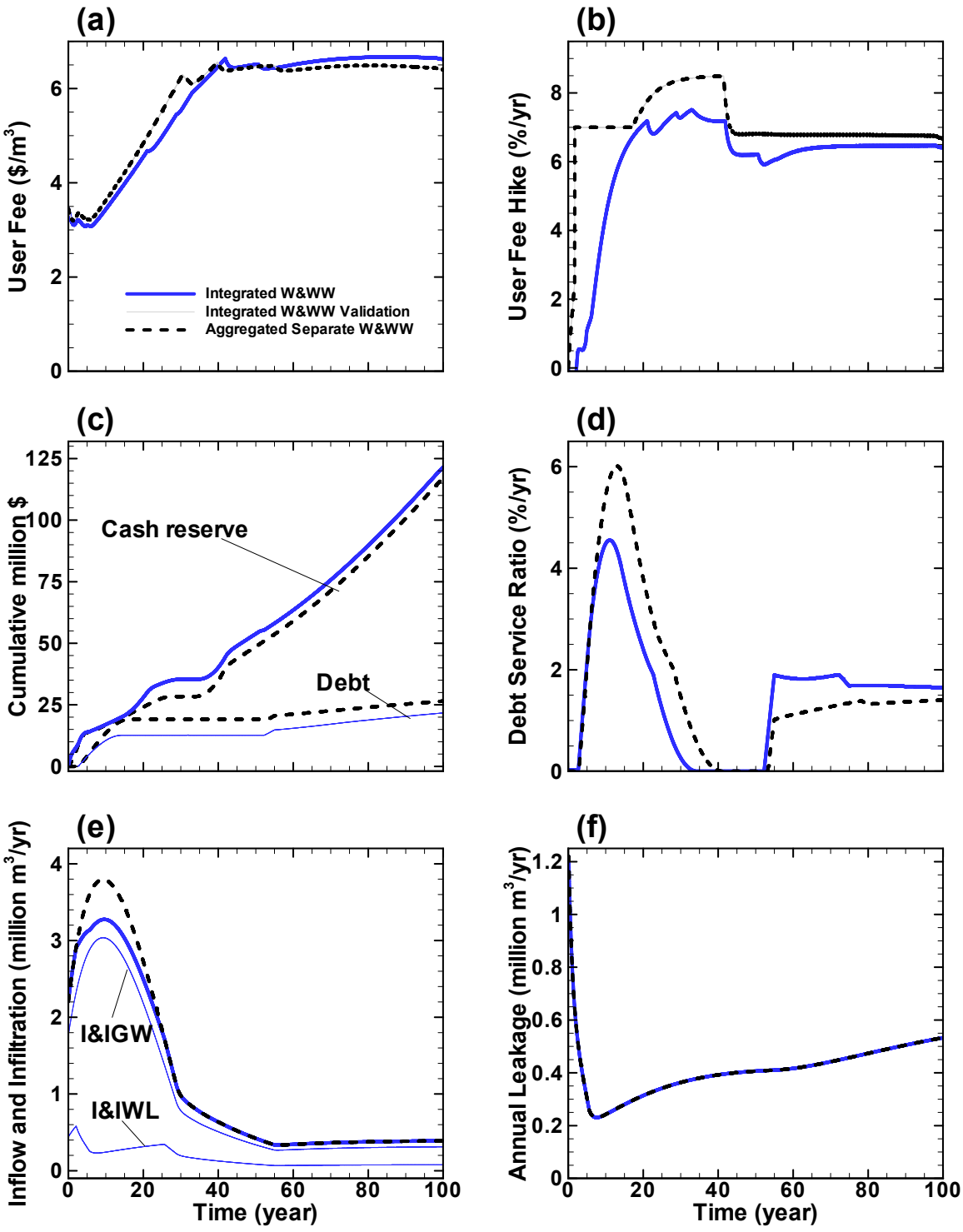
Cumulative cash reserve and debt over 100 years planning horizon are presented in Figure 5.9c for integrated W&WW and aggregated-separate W&WW models. In general, the results show an increasing trend for both models. The cash reserve starts with a value of $million\ \$0$ for both models, followed by some curvatures in the first 40 years, and continues to increase linearly to the end of simulation period to reach the final values of $million\ \$122\ and\ \$117$ for integrated W&WW and aggregated-separate W&WW models, respectively.

Figure 5.9d shows debt service ratio as percentage of annual revenue for the borrowing scenario. In general, debt service ratio shows similar trend for both models. For integrated W&WW model, it starts with a value of 0%, increases to reach its peak value of 4.5% at 10 years, declines to 0% at 34 years, and remains constant for 18 years, follows by a rapid increase, and continues to increase to reach the value of 1.65% at 100 years (Figure 5.9d). For aggregated-separate W&WW, it starts with a value of 0%, increases to reach its peak value of 6% at 13 years, declines to 0% at 40 years, and remains constant for 13 years, follows by a rapid increase, and continues to increase to reach the value of 1.4% at 100 years (Figure 5.9d).

The total annual volume of inflow and infiltration ($I\&I$) starts with a value of $million\ 2.2\ m^3/year$ for both models. Due to ICG 4 sewer pipes moving to ICG 5 pipes, annual volume of $I\&I$ increases to reach its peak value of $million\ 3.2\ m^3/year$ and $million\ 3.8\ m^3/year$ at 10 years for integrated W&WW and aggregated-separate W&WW models, respectively, drops to

$million\ 0.4\ m^3/year$ at 60 years for both models due to the optimal policy levers of 1) no more than 10% fraction of ICG 5 pipes, and 2) desired elimination period of 10 years, and remains constant to the end of simulation period (Figure 5.9e). Once again, the volumes of $TotalI\&I$ is measured based on two sources: 1) ground water (GW), and 2) water leakage (WL), as noted in Section 5.4.1.

The annual volume of leakage starts with a value of $million\ 1.2\ m^3/year$ for both models, drops rapidly to $million\ 0.25\ m^3/year$ at 5 year, due to the optimal policy levers of 1) no more than 5% fraction of highly deteriorated pipes (75+ years), and 2) desired elimination period of 5 years, follows by a linear increase due to the increase in the length of PVC water main (75+ years) to the end of simulation period, to reach the value of $million\ 0.53\ m^3/year$ for both models (Figure 5.9f).



Note: *W*, water; *WW*, wastewater

Figure 5.9**:** System dynamics modeling results over a 100-year simulation period

5.6.2 Discussions

Using data from a Canadian municipality, the integrated SD model and the two separate water and wastewater SD moles are simulated and compared over a 100-year planning horizon. A capital reserving management strategy (i.e., annual cash reserve as percentage of the network value) is used for asset management of the water distribution network, and a borrowing management strategy (i.e, issuing debt) is used for asset management of the wastewater collection network. The utility's desired cash reserve is set at 4% of the water distribution network asset value per year. For the integrated SD model, the cash reserve accumulates into the integrated fund balance account. The integrated finance sector also accumulates incomes received from the water and wastewater utilities into one account. Hence, due to the integration of the utilities financial resources, the financial capacity of the integrated SD model is increased which enables the utility to accelerate operational, maintenance and capital works in order to enhance the integrated service level of the assets.

The simulation results indicate that in the first 52 years, user fee for the integrated SD model is cheaper compared to the aggregated-separate SD model (Figure 5.9a). This is due to increase in financial capacity of the integrated model. The integrated SD model's user fee becomes slightly greater than the aggregated-separate SD model's user fee beyond 52 years due to increase in debt service ratio (Figure 5.9d). This is due the fact that the integrated SD model shifts borrowing compared to the aggregated-separate SD model because of access to a larger financial resource as discussed above.

5.7 Conclusions

Based on this study, the following conclusions can be drawn:

1- A causal loop diagram is developed to lay out the connection points and identify the interacting feedback loops that exist among the infrastructure, finance and socio-political sectors.
2- The system dynamics modeling is applied to develop a decision support tool for the integrated asset management of water distribution and wastewater collection systems. The developed model is the first known integrated approach for asset management of the water

and wastewater infrastructure systems. The model data requirements and specific tests and procedures to validate the integrated SD model are elaborated.

3- The integrated SD model is validated and implemented using data from one utility in Southern Ontario, Canada. The simulation results over a 100-year planning horizon indicate that the integrated SD model can enable the utility to enhance the infrastructure, financial and socio-political performance of their water and wastewater assets relative to managing these assets in isolation.

4- In practice, the developed SD model should enable the water utility's stakeholders to evaluate various decision-making policies and financing strategies for the long-term integrated asset management of water distribution and wastewater collection networks.

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Chapter 6
Conclusions, Contributions and Future Recommendations

6.1 General Conclusions

Specific conclusions for various aspects of this research are listed in each of Chapters 2 to 5 under section conclusions. A general summary of conclusions for the research is presented below.

Three categories of normalized and time-integrated benchmarking performance indicators (BPI's) are developed that conform to the four themes of strategic target, policy lever, sustainability, and life cycle. BPI's will allow water utilities with different attributes, such as: pipe inventories (materials, condition and length); customer characteristics (population, consumption and conservation patterns); and, financial characteristics (allowable fee-hike rate, water fee, funds), to benchmark their asset management and financial position relative to one another.

The application of the entire set of BPI's using the outputs of the advanced water and wastewater system dynamics models demonstrates the complexity of water distribution and wastewater collection systems. It also indicates how the BPI's can be used to benchmark a utility's performance relative to other utilities to forecast the future behaviour of the system and to peruse decision-making policies for improvements and best practices.

A causal loop diagram is a graphical tool to qualitatively identify interactions and feedback loops involved in the integrated asset management of water distribution and wastewater collection networks. Furthermore, a causal loop diagram can be translated to a mathematical simulation model, to explicitly model the feedback mechanisms among various components of the integrated system and thus provides an opportunity to understand the integrated dynamic behavior of the system.

Simulation results show that utilities can implement different financial strategies (pay-as-you-go, borrowing, capital reserving) and decision-making policies for improvements and best practices, and to sustainably meet strategic targets over the life cycle of assets.

6.2 Contributions

This research makes the following original contributions to the state of knowledge:

1. A set of normalized and time-integrated benchmarking performance indicators (BPI's) are developed that are grouped into three categories of 1) infrastructure, 2) socio-political, and 3) financial;
2. The Rehan et al.'s (2013; 2015) water distribution system dynamics (SD) model, and the Rehan et al.'s (2014a; 2014b) wastewater collection SD model are advanced to address their associated limitations. Different fundamental financing and rehabilitation strategies are explored and compared for asset management of water distribution and wastewater collection networks;
3. An implementation framework for asset management strategy of each water distribution and wastewater collection networks is developed that contains three decision-making layers: 1) visions & values, 2) function (i.e., advanced SD models), and 3) performance (i.e., BPI's);
4. A Causal loop diagram is developed to demonstrate the complexity, interactions and feedback loops that exist among the components of the integrated water distribution and wastewater collection networks;
5. A system dynamics model is developed for the integrated asset management of water distribution and wastewater collection networks. The model includes a variety of infrastructure, socio-political and financial policy levers;
6. Critical data elements are identified which need to be collected and recorded by water and wastewater utilities.

The benchmarking performance indicators and asset management models developed in this research can be used by various water and wastewater utilities' stakeholders to negotiate and enact meaningful strategic targets and policy levers that lead to the sustainable management of the water distribution and wastewater collection networks.

6.3 Recommendations and Directions for Future Research

The most important contribution of this research is that it presents an innovative framework that facilitates holistic planning for water utilities to implement strategic-level policy levers that enable them to achieve sustainable infrastructure, social-political, and financial performance over the life cycle of the water distribution and wastewater collection networks. Furthermore, using the underlying conceptual ideas of this framework, it is possible to further refine and expand the scope of the presented benchmarking performance indicators and asset management models for water distribution and wastewater collection networks. Specific recommendations for future research work are listed as follows:

- Research is needed to develop additional BPI's for the entire water infrastructure systems including water and wastewater treatment plants to demonstrate their long-term sustainability over the life cycle of assets.
- Develop a holistic strategic asset management model by introducing infrastructure and financial sectors for water and wastewater treatment plants, and incorporating these sectors into the integrated asset management model for water distribution and wastewater collection networks presented in this thesis. This can enable water utilities' decision makers to better understand the complexity and interactions that exist among the infrastructure, financial, and socio-political sectors of the entire water infrastructures systems including water distribution, wastewater collection, and water and wastewater treatment plants.
- Viewing water and wastewater infrastructure systems from a network or functional viewpoint down to an individual component is critical from life-cycle management viewpoint. Further research is needed to develop tactical (2-10 years) and operational (1-2 years) planning models for the integrated asset management of water infrastructure systems in order to link (vertical integration) and share data efficiently among the strategic, tactical and operational asset management plans.
- Develop a database management system to support efficient sharing and management of data and planning information among strategic, tactical and operational plans, and to enable the integration and interoperation of various domain-specific software applications through developing and maintaining vertical integrated asset management plans. The vertical

integration framework can be comprised of a comprehensive database of water and wastewater infrastructure asset inventory, financial and socio-political sectors that analyses and stores data through strategic, tactical, and operational (STO) planning. An Integrated Water Infrastructure System (IWIS) database can store and manage flow of information among strategic, tactical, and operational models. Also, data can be identified by reference of time and/or date (temporal) and by physically relation of data to the location of a facility in the infrastructure network (spatial).

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