Life cycle sustainability assessment of asset management plans for municipal wastewater systems

by

Hamed Mohammadifardi

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Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner:

Dr. Steve Conrad

Supervisors:

Dr. Mark Knight
Associate Professor, Department of Civil and Environmental Engineering

Dr. Andre Unger
Associate Professor, Department of Earth and Environmental Sciences

Internal Committee Member

Dr. Chris Bachmann
Assistant Professor, Department of Civil and Environmental Engineering

Dr. Rebecca Saari
Assistant Professor, Department of Civil and Environmental Engineering

Internal-external Committee Member

Dr. Neil Brisley
Associate Professor, School of Accounting and Finance

Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the 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.

Statement of Contribution

Section 4.1 of Chapter 2 and Section 2.2.1.4 of Chapter 4 of this thesis have been incorporated in a published paper which was co-authored by myself and my supervisors, Dr. Mark Knight and Dr. Andre Unger. A simple version of the causal loop diagram which is described in Section 2 of Chapter 3 of this thesis have been introduced and incorporated in another published paper which was co-authored by myself and my supervisors.

The system dynamic model developed by a former PhD student, Dr. Rashid Rehan (an Associate Professor at the University of Engineering and Technology, Peshawar), and my supervisors, Dr. Mark Knight and Dr. Andre Unger, is used as a basis for modelling the wastewater collection pipe asset management plan presented in Section 5.2.2 of Chapter 2 of this thesis. Their model is developed further to include population growth, urban development, and GHG emissions from wastewater collection and treatment systems.

Abstract

Municipal governments have the responsibility to provide safe drinking water and handle polluted water to protect their citizen's health and safety. Maintaining water infrastructure systems, including wastewater collection pipes and wastewater treatment plants, is essential to sustain these vital services.

To date, all municipalities in Ontario have developed an asset management plan to coordinate capital and operational activities required for sustaining their water infrastructure. (Ontario Ministry of Infrastructure 2017b). While this is great progress, significant differences exist among municipalities in terms of the methodology and level of completeness used in developing their asset-management plans (Ontario Ministry of Infrastructure 2017a).

In this research, a novel sustainability assessment framework is proposed and demonstrated as part of the solution to establish a complete model framework for sustainable asset management planning. A system-dynamic based sustainability-assessment tool is adapted to evaluate the impact of population growth and urban development on wastewater asset-management planning decisions.

The importance of system boundary definition in the proposed framework is demonstrated by evaluating the sustainability impact of strategic decisions in asset management planning for a case study exploring a wastewater collection system. In doing that, a novel system-dynamic model for wastewater-collection and wastewater-treatment plant systems are developed, and the interactions between these two assets are graphically illustrated. The results highlight the significance of coordinating asset management plans of neighboring infrastructure in achieving progress toward sustainable asset-management planning.

It is hoped that the application of the proposed framework can help decision makers in municipalities to comply with existing and changing regulatory policies and requirements and to develop socially acceptable, environmentally friendly and financially viable asset-management plans.

Acknowledgements

I would like to express my sincere gratitude and deepest appreciation to my supervisors Dr. Mark Knight and Dr. Andre Unger for their kind advice and exceptional mentorship throughout my PhD program. This research truly benefited from their constant encouragement and support of my ideas. I am also thankful to Dr. Chris Bachmann, Dr. Rebecca Saari, and Dr. Neil Brisley as my committee members, for reviewing of my research proposal and thesis and for offering insightful comments. It is a privilege to have Dr. Steve Conrad as my External Examiner and reviewer of my thesis, and I am very grateful.

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I would also like to acknowledge the City of London, City of Niagara Falls, and City of Waterloo for making available their data for this research. Many staff members in these cities, especially Mr. Kevin Graham, Mr. Roland Welker, Ms. Denise McGoldrick 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 to my dear parents for their encouragement and for all of their warmth and care. My heartfelt gratitude goes to my wife for her love, companionship and patience throughout our amazing journey.

Dedication

To my beloved wife, Razieh,

and my parents,

for their love, support, and encouragement in every step of my life.

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Chapter 1

Introduction

1.1 Background

The government of Canada has committed to and established strategic objectives to move the country toward economic, social, and environmental sustainable development. As one step, it appointed an advisory council and constituted an office for the development and implementation of the Federal Sustainable Development Act (2008). More recently, the Federal Sustainable Development Strategy (FSDS 2016) has been developed as a vehicle for planning and reporting to the government of Canada the sustainable development priorities, goals, and actions from 41 federal organizations. The government's strategies have further trickled down into various jurisdictions and organizations, including civil and environmental engineering ones. In particular, leadership in sustainable infrastructure development has become one of the three main strategic goals of the Canadian Society of Civil Engineering (CSCE).

In addition to the increasing interest in sustainable development, the intrinsic need to rejuvenate deteriorated urban infrastructure has motivated sustainable urban infrastructure planning. Specifically, the Federation of Canadian Municipalities (FCM) has promoted a guidebook under the Leadership in Asset Management Program (LAMP), to support municipalities in integrating sustainability considerations into their asset management policies and strategic plans (FCM 2017). These legislative frameworks and guidelines are leveraged by economic incentives and programs, such as the Green Municipal Fund (GMF) and the Municipalities for Climate Innovation Program (MCIP) provided by FCM.

A specifically Canadian model framework is being developed by the National Round Table on Sustainable Infrastructure (NRTSI) and the National Research Council (NRC) to create a unified approach to assessing the condition state, performance, and management of the country's core public infrastructure assets (Felio and Lounis 2009). The International Standard Organization (ISO) provides definitions, standard requirements, and a checklist of good practices for developing asset management programs in its ISO-55000 series (ISO 2014).

These retrospective assessment frameworks apply various indicators to ‘check’ the performance of asset management plans on a continual Plan-Do-Check-Act asset management cycle presented in the ISO 55000 Asset management framework (Figure 1-1) to help decision makers in acting upon deficiencies found in the previous planning cycle. However, such frameworks are not specifically designed to appraise the future performance of asset management decisions. Therefore, ‘sustainability assessment’ tools are needed to project the performance of assets onto their future life-cycle and to inform decision makers to develop sustainable asset management plans in an iterative process.

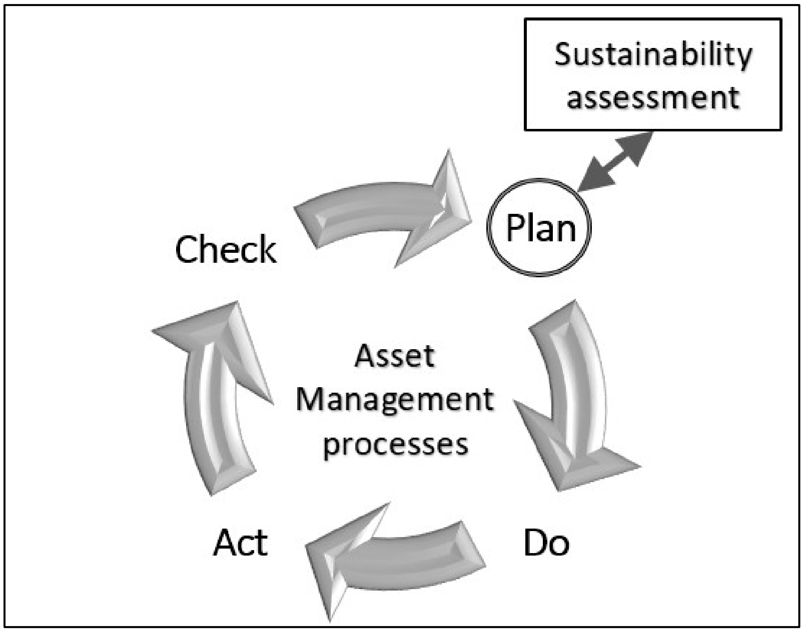


Figure 1-1: Application of the proposed sustainability assessment tool in ISO 55000 (ISO 2014) asset management framework.

Commercial software such as RIVA, Hansen, InfraModex, MIMS, Synergen, IBM Maximo, Infrastructure 200 and Harfan are examples of existing software packages used in the corporate asset management industry. The majority of these tools focus on day-to-day work-order planning at the operational level, and rarely have been developed to support long-term and strategic life-cycle asset management planning (Halfawy et al., 2006).

Recently, Rehan (2011) and Ganjidoost (2016) developed and applied system dynamic (SD) simulation techniques to model the functional and financial performance of asset management plans for water and wastewater infrastructure systems over their life cycle. Simulation of the future condition of pipe-network systems and projection of subordinated operational and capital costs allowed them to evaluate management strategies for rehabilitating and replacing urban water and wastewater pipe-network systems while pursuing financial sustainability goals.

1.2 Problem Statement

A complete sustainability assessment, as described by Sala, Ciuffo, and Nijkamp (2013), should assess all dimensions of sustainability, i.e., economic, social, environmental; deal with non-linearity and dynamic features, and include the consequences on upstream and downstream processes, i.e., water distribution and wastewater treatment plant (WWTP) systems respectively.

The current studies on sustainable asset management planning often consider the environmental, economic, and social components related to urban water and wastewater in isolation from one another. Moreover, the dynamic interactions and feedback between urban water and wastewater systems are not considered in current sustainability assessment approaches (Upadhyaya 2013).

The primary concern of previous SD models was projecting future costs for achieving the goal of financial self-sustainability, without considering the social and environmental dimensions. Therefore, other non-physical issues such as population growth and urban densification are not investigated in the available SD models. Moreover, these SD models are developed only for linear water distribution and wastewater collection systems separated from other infrastructure such as treatment-plant systems. Therefore, the associated dynamic variations and financial concerns are not integrated with their models.

1.3 Research Goal and Objectives

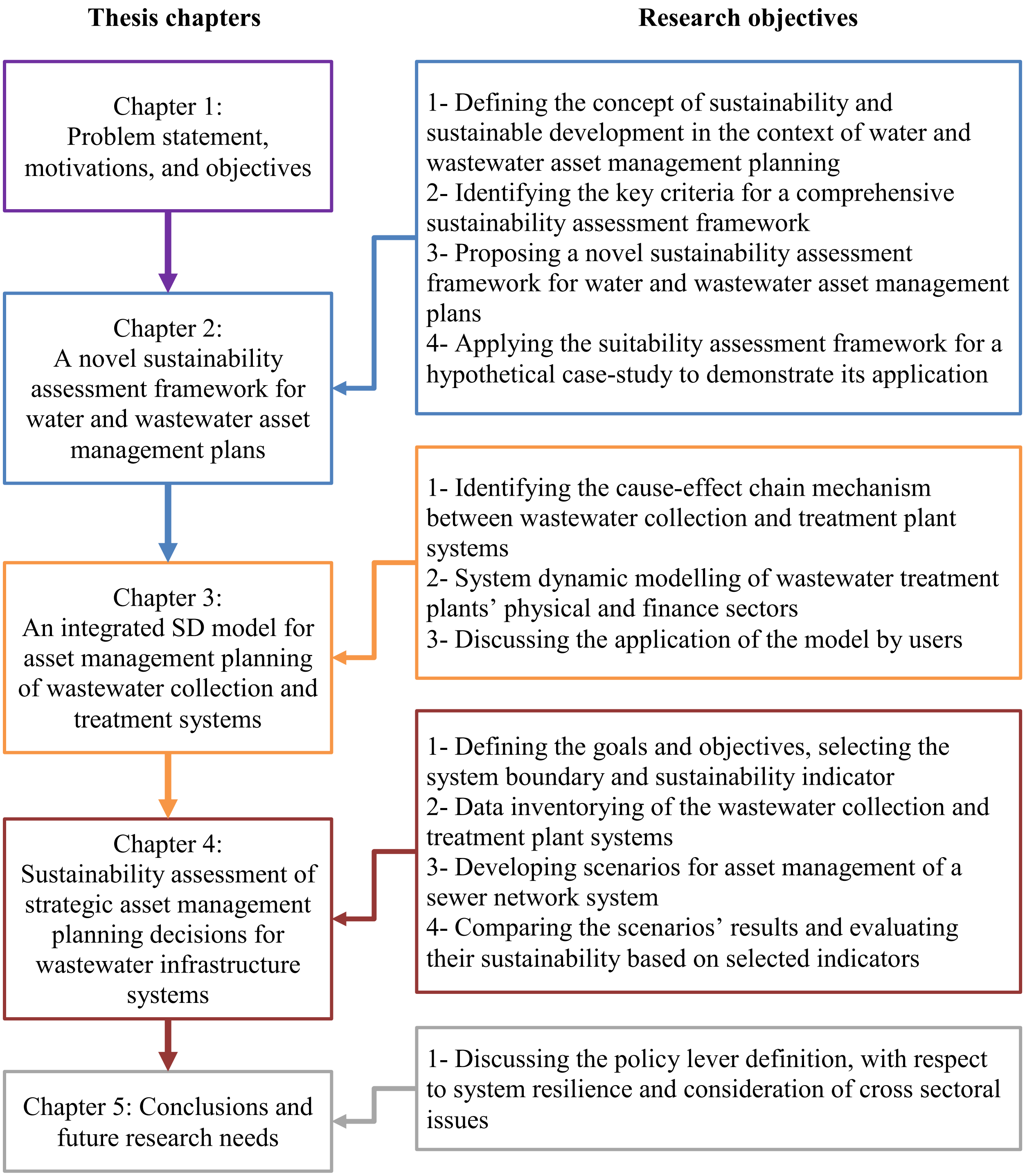
The overall goal of this research is to propose a novel framework for comprehensive sustainability assessment of water and wastewater asset management plans and demonstrate its application merits in a real case study project.

This goal is achieved by pursuing the following five specific research objectives:

1. Define the sustainability concept and its implications within an urban water and wastewater asset management planning context. This common understanding of a sustainability concept constitutes a complete sustainability assessment for water and wastewater asset management plans.
2. Review the available frameworks and depict the current state of relevant research. This literature review is needed to identify the research gaps and build a novel contribution beyond that of previous research work.
3. Propose a novel sustainability assessment framework that evaluates the physical, social, environmental and financial sustainability of asset management plans and captures their dynamic feedbacks.
4. Build a SD model for the simulation of integrated wastewater collection and treatment plant systems. To achieve this fourth objective, a causal loop diagram should be developed to demonstrate the interconnections and feedback mechanisms between the different components of the physical, economic, consumer and environmental sectors.
5. Demonstrate the application of the proposed framework and apply the developed SD model using a case study of an existing wastewater infrastructure system. This case-study demonstration is required to gain empirical knowledge on the utility of the framework as implemented in the SD model.

1.4 Thesis Organization

This thesis is organized in an integrated-article format – that is, each of Chapters 2 to 4 addresses one or several of the above listed research objectives. Figure 1-2 presents a graphical summary of the remainder of the thesis chapters and the main research tasks performed in each of them.



Chapter 1:
Problem statement, motivations, and objectives

Chapter 2:
A novel sustainability assessment framework for water and wastewater asset management plans

1- Defining the concept of sustainability and sustainable development in the context of water and wastewater asset management planning
2- Identifying the key criteria for a comprehensive sustainability assessment framework
3- Proposing a novel sustainability assessment framework for water and wastewater asset management plans
4- Applying the suitability assessment framework for a hypothetical case-study to demonstrate its application

Chapter 3:
An integrated SD model for asset management planning of wastewater collection and treatment systems

1- Identifying the cause-effect chain mechanism between wastewater collection and treatment plant systems
2- System dynamic modelling of wastewater treatment plants' physical and finance sectors
3- Discussing the application of the model by users

Chapter 4:
Sustainability assessment of strategic asset management planning decisions for wastewater infrastructure systems

1- Defining the goals and objectives, selecting the system boundary and sustainability indicator
2- Data inventorying of the wastewater collection and treatment plant systems
3- Developing scenarios for asset management of a sewer network system
4- Comparing the scenarios' results and evaluating their sustainability based on selected indicators

Chapter 5: Conclusions and future research needs

1- Discussing the policy lever definition, with respect to system resilience and consideration of cross sectoral issues

Figure 1-2 Thesis chapters organization and objectives.

Chapter 2 develops a novel framework for life cycle sustainability assessment of policies and strategic decisions for water and wastewater infrastructure asset management. This interdisciplinary research resulted from an integrative literature review pertained to the three areas of life-cycle assessment, sustainability assessment, and SD modeling in the context of urban water and wastewater infrastructure systems. The proposed framework is implemented to evaluate population growth and urban densification impacts on the sustainability of asset management decisions for a hypothetical wastewater collection pipe-network system.

Chapter 3 describes a detailed causal loop diagram and a SD model for the integrated asset management of municipal wastewater collection pipe networks and treatment plants systems. The parametrized variables within the financial, social, and environmental sectors related to the physical wastewater collection and treatment plant sectors are described and modeled in the Stella software. The model interface-layer of the model, including the date-entry tables, key policy levers used for defining scenarios, and key output parameters used for evaluating simulation results, are presented.

In Chapter 4, the SD model is employed to assess the sustainability of strategic decisions for asset management planning for the wastewater infrastructure systems of a medium-size municipality in Southern Ontario. Alternative scenarios are developed to compare how an accelerated rehabilitation of wastewater collection pipe-network system, on a pay as you go finance strategy, affects social, environmental, and finance systems.

A general summary of all the chapters' conclusions, the original contributions to the state of knowledge, and directions for future research are presented in Chapter 5.

Chapter 2

Sustainability assessment of municipal wastewater asset management plans

Abstract

Several frameworks have been promoted to define and establish standard requirements in sustainable asset management planning. However, significant differences in terms of completeness and the methodology used to develop asset management plans still existed among municipalities in Ontario (Ontario Ministry of Infrastructure 2017a). These differences will be extended as new aspects related to sustainable asset management planning are realized and amended to the current regulatory schemes. This chapter critically reviews the current tools developed for sustainability assessment of municipal water asset management plans and evaluates their strengths and shortcomings in framing a complete sustainability assessment. The concept of sustainability within the water and wastewater asset management context is explored to tackle the inconsistencies in definitions, and a novel sustainability assessment framework is presented that reconciles the different approaches and captures the required criteria for a complete sustainability assessment. Moreover, the key issues in applying the proposed framework in the sustainability assessment of municipal water and wastewater systems are presented in a case-study demonstration.

Keywords: asset management, life-cycle assessment, sustainability assessment, water and wastewater asset, municipal water and wastewater infrastructure system

2.1 Introduction

Canadian Municipalities have complied with regulatory objectives for many years in providing clean drinking water to citizens and handling their wastewater. However, as the majority of water distribution and wastewater collection (WWC) networks in Canada were built many years ago and have been poorly maintained, they are rapidly deteriorating and become increasingly expensive to operate. This situation is of concern for both budgetary and public health reasons. Replacement of these networks will need significant capital–an estimated $138 billion CND (Canadian Infrastructure Report Card 2012). Yet, meeting new demands for growing urban areas in terms of expanding the water distribution and wastewater collection networks and building new treatment capacities also needs investment.

New regulations and directives at the federal and provincial levels are set to direct municipalities toward sustainable infrastructure asset management, which is defined as "the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems over their lifecycles" (PAS 2008). Since 2010, the Water Opportunities and Water Conservation Act (WOWC 2010) has required all water and wastewater utilities in Ontario to prepare long-term asset management plans for their physical infrastructure. It also obliges water utilities to have a water conservation plan that promotes the efficient use of water and reduces negative impacts on water resources. Other regulations and directives are in place to guide municipalities on reducing their environmental footprints and financial reliance on governmental subsidies.

The Green Energy Act of 2009 (Green Energy Act, 2009) requires public agencies, including municipalities, to prepare an energy conservation and efficiency strategy when planning their capital investments. Ontario regulation 452/09 requires reporting from facilities that emit more than 2,500 tonnes of GHG per year. Over 300 municipalities in Canada are joined in the Partners for Climate Program (PCP), to take local action to reduce the GHG emissions from their operations and services, including water and wastewater infrastructure. The Safe Drinking Water Act (MOE 2002) requires that water and wastewater utilities prepare financial plans to cover their anticipated cost for water services. In 2006, the public sector accounting group of the Canadian Institute of Chartered Accountants issued PS3150 standard (CICA 2007) to help governmental bodies, including water and wastewater utilities account for the value and cost of their tangible capital assets when preparing their financial statements.

Complying with existing and changing regulatory policies and requirements, and developing socially acceptable, environmentally friendly and financially viable asset management plans is a major challenge that calls for comprehensive sustainability assessment. As part of a solution for sustainable asset management planning, this thesis propose a novel sustainability assessment framework that applies system dynamics (SD) and life-cycle assessment (LCA) tools to project and evaluate the future performance of water and wastewater infrastructure systems. It also explores the key issues in practical application of the proposed framework, illustrated on a hypothetical municipal wastewater infrastructure system.

2.2 Sustainability concept

Defining the terminologies and establishing a common understanding of issues related to sustainability in municipal water and wastewater infrastructure systems is essential for the development of a sustainability-based asset management plan.

The first notion of sustainable development was concerned with the impacts of population growth and was acknowledged in books such as Rachel Carson's *Silent Spring*, (1962), Edward Goldsmith's *Blueprint for Survival*, (1972), Paul Ehrlich's *The Population Bomb*, (1971), and the report of Massachusetts Institute of Technology (MIT) to the "Club of Rome" known as "The Limits to Growth", (1972). The key conclusion of the last was that if the current trend in population growth and consumption continues for another century, the threshold for extracting resources from earth will be reached; consequently, the human population and its built industrial capacity will collapse (Clarke 1994).

The widely accepted definition of sustainable development from "Our Common Future" –also known as the Brundtland report (1987) –states that "sustainable development implies development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Although the definition of sustainability in the Brundtland report does not consider exactly what area of science pertains to sustainability, the concept became an inclusive term that embraced environmental, social and economic development. In later research, connections between the three areas of sustainability have been recognized, referred to as the triple bottom line by John Elkington (1994).

2.2.1 Sustainability of urban water and wastewater systems

The transmission of sustainability concepts into political debates can be linked to the United Nations Conference on Environment and Development (UNCED) called “the Earth Summit” in Rio de Janeiro in 1992. Following that conference, several documents were published, including an action agenda known as Agenda 21 (UN 1992), where an overall strategy for sustainable urban water development is presented as “the identification and implementation of strategies and actions to ensure the continued supply of affordable water for present and future needs and to reverse current trends of resource degradation and depletion” (UN., (1992) Agenda 21, Chapter 18th, 5th program, 18-57, p 213). The related guiding principles concerned with the sustainable water and wastewater infrastructure assets highlight “sound financial practices, achieved through better management of existing assets, and widespread use of appropriate technologies” (UN., (1992) Agenda 21, Chapter 18th, 4th program, 18-48, p 210).

The key points in the above definitions stress the notion of multiple areas of sustainability, that is, financial, social, and environmental sustainability; attention to “present” and “future generations’ needs”, which highlights the intergenerational equity and life-cycle thinking principals in sustainable development; and the need to develop existing as well as new assets.

2.3 Review of sustainability assessment frameworks

In the realm of sustainability assessment, several indicators and tools have been developed to assess the sustainability of urban water and wastewater systems (Xue et al. 2015). Each indicator or tool–may be quantitative or qualitative–has a particular strength or focus in describing or predicting the impacts on sustainability (Singh et al., 2012). Among these developments, frameworks are procedural tools structured by various indicators, or analytical tools for systematic sustainability assessment (Finnveden and Moberg 2005).

The relevant literature has been reviewed to identify research gaps in proposed sustainability assessment frameworks for water and wastewater infrastructure systems. Five key criteria suggested by Sala, Ciuffo, and Nijkamp (2013) are used to critically review the current sustainability assessment frameworks. As presented in Table 2-1, a complete sustainability assessment framework should assess all the dimensions of sustainability (economic, social, environmental), deal with any non-linearity and dynamics features of the system, have a system-wide perspective to include all life-cycle stages, support scenario development, and include consequences on downstream and upstream systems.

Table 2-1: Available frameworks for sustainability assessment of urban water and wastewater infrastructure systems.

References ***Criteria***	***Hellström et. al., (2000)***	***Sahely et al., (2005)***	***Murray etl al., (2009)***	***Sharma et. al., (2009)***	***Rehan et. al., (2011)***	***Beheshti et. al., (2018)***
Value Choices:						
- Mentions values explicitly	✓	✓	✓	✓	✓	✓
Completeness of scope:						
- Assesses all dimensions of sustainability	✓	✓	✓	✓	✗	✗
- Encompasses system-wide analysis	✓	✓	✓	✓	✓	✓
- Considers limits of resources and carrying capacity	✓	✓	✓	✓	✗	✗
- Deals with non-linearity, and dynamic feedback	✗	✗	✗	✗	✓	✗
Strategic view:						
- Defines the decision context clearly	✓	✓	✓	✓	✓	✓
- Supports scenario development and assessment	✓	✓	✗	✗	✓	✓
- Includes upstream and downstream consequences	✗	✗	✗	✓	✗	✗
Methodology:						
- Is scientifically robust and deals with uncertainties	✓	✓	✓	✓	✓	✓
- Has applicability, data availability, comparability, and transparency	✓	✓	✓	✓	✓	✓
- Can deal with cross-sectorial issues	✗	✗	✗	✗	✗	✗
Participation of stakeholders:						
- Has the capability of integrating different perspectives and interacting with stakeholders	✓	✗	✗	✓	✓	✓

For methodological competency, the framework should be applicable in terms of data availability, comparability and transparency. It should also have scientific robustness and the ability to deal with uncertainties and cross-sectoral issues (Sala, Ciuffo, and Nijkamp 2013).

The literature review result reveals that only Rehan et al. (2011) have dealt with the non-linearity and dynamic feedback in the sustainability assessment of water and wastewater systems. However, system-wide analysis, and a life-cycle thinking approach in particular, were included in all the reviewed frameworks.

Municipal water and wastewater infrastructure systems are integrated components of an urban infrastructure system, and perform synergistically with other municipal assets such as energy and transport infrastructure systems (Sahely, Kennedy, and Adams 2005). None of the reviewed frameworks has included the sustainability impact of water and wastewater asset management plans on other urban infrastructure systems, or vice versa.

2.4 Toward a novel and comprehensive sustainability assessment framework

The important question in sustainability assessment is to decide which tool or framework is more appropriate for a given application. The ethical implication lies in the fact that, by selecting a certain tool, “the analyst ‘subscribes to’ and in effect ‘enforces’ a specific worldview as the correct or most appropriate yardstick to measure the sustainability” of a project, plan, or policy (Alexandros Gasparatos 2010). Of course, if those values are unacceptable or even irrelevant to stakeholders, the assessment will be useless. For instance, the financial sustainability plan of a water provisioning service will fail if the analyst assumes that a water user will pay any price to be connected to the water service. In contrast, subsidizing water and wastewater services so as to leave no reason for not connecting to these services and reducing public health risks will undermine the financial sustainability goal.

Gasparatos and Scolobig (2012) suggest four general approaches in selecting sustainability assessment tools: 1) based on the desired perspective of sustainability assessment; 2) based on the desired feature of sustainability assessment; 3) according to the acceptability criterion; and, 4) according to the values of affected stakeholders (Table 2-2).

Table 2-2: Sustainability-assessment-tool selection criteria.

Bases for selecting the sustainability assessment tools	*Examples*
According to the desired perspective of assessment	Eco-centric Anthropocentric
According to the desired feature of assessment	Integrative or triple-bottom-line , Predictive or ex-ante assessment, Inter- or intra-generational equity, Based on participatory approach
According to the acceptability criterion	Maximum sustainability, Non-negative overall sustainability, Target oriented sustainability state
According to the values of affected stakeholders	Social-altruistic, Biospheric, Egoistic

As mentioned in Section 2.2.1, the goal of sustainable water and wastewater asset management plans is to maintain affordable services for current and future generations, while reversing environmental-degradation and resource-depletion trends. Therefore, the desired perspective on the sustainability of urban water and wastewater system pertains to both anthropocentric and eco-centric views.

The desired features of a sustainability assessment framework relate to the criteria presented in Section 2.3 for complete sustainability assessment, including assessment of all areas of sustainability for current and future life cycles of the asset and dealing with non-linearity and the dynamic feedback of social, ecological, and economic systems. Therefore, the dynamics and inter-relations between the socio-economic and techno-physical systems related to water and wastewater asset systems, as presented in Rehan (2011), compel an integrative sustainability assessment.

The other feature of sustainability assessment are to predict the future sustainability impacts of decisions taken in asset management planning processes, and to consider the intergenerational equity from both financial and ecological perspectives. Finance strategies such as borrowing or capital reserving for either current or future capital investments can distribute the investment costs across all generations of service users, whereas the pay-as-you-go strategy with conventional economic efficiency considerations will put the capital costs on current users.

The provision of drinking water from renewable resources and their pollution prevention supports the intergenerational equity from the ecological view point.

The acceptability of asset management plans are based on achieving the desired or expected level of services. Therefore, the targeted sustainability state should be used for sustainability assessment. Moreover, the water and wastewater assets are managed for public services and not for any individual's interest. This means that the values of stakeholders are neither merely biospheric nor egoistic, but social-altruistic.

2.4.1 Dynamic life-cycle sustainability assessment

Dynamic behavior and complexity of urban water system have been articulated by many scholars. For example, Grigg and Bryson (1975) demonstrated the interconnections between population growths, urban area development, and utilities' finance system in their simulation model. Biachia and Montemaggiore (2008) modeled the dynamics and interdependencies between key financial indicators, customer satisfaction, and the bargaining power of water utilities. Adeniran and Bamiro (2010) used system dynamic modeling to assess the impact of population growth, water availability and energy cost in strategic planning of water supply system. Recently, Rehan et al. (2015) and Ganjidoost et al. (2018) modeled various interconnections and feedback between the physical, financial, and consumer sectors for strategic asset management planning of linear water and wastewater infrastructures.

Modeling the non-linearity and dynamic feature of social, ecological and economic systems is one of the important features of a complete sustainability assessment framework. Nevertheless, these aspects are rarely modeled or considered in the frameworks reviewed in Section 2.3. Socioeconomic tools, such as system dynamics (SD) modeling can be applied together with the environmental life-cycle-assessment (LCA), social-LCA and life-cycle-cost (LCC) assessment tools to model the interconnections between all areas of sustainability (Halog and Manik 2011). Such an integrated perspective on economic, social and environmental issues provides a comprehensive sustainability assessment tool and avoids favoring a particular issue in the interest of a specific stakeholder (Changsirivathanathamrong, Moore, and Linard 2007).

SD is a versatile tool for modeling and assessing the socio-economic impacts of implementing strategic decisions. It was developed by Jay Wright Forrester during the mid-1950s, and has been extensively employed to model the constituents and structure of dynamic industrial systems to predict the cause-effect chains and feedback mechanisms within socio-economic systems. The SD modeling tool brings in the dynamic characteristics missing from the LCA framework, and adds the benefit of time progression in the sustainability assessment. It is used as a platform for modeling and integrating LCA tools such as water-footprint analysis, life-cycle energy analysis, carbon-footprint analysis, and LCC analysis, as presented in Figure 2-1. On the other hand, the LCA tool provides a set of quantitative environmental indicators and broadens the scope of SD modeling to examine all the "cradle to grave" processes and so avoid the sub-optimization and problem shifting pitfalls in the assessment.

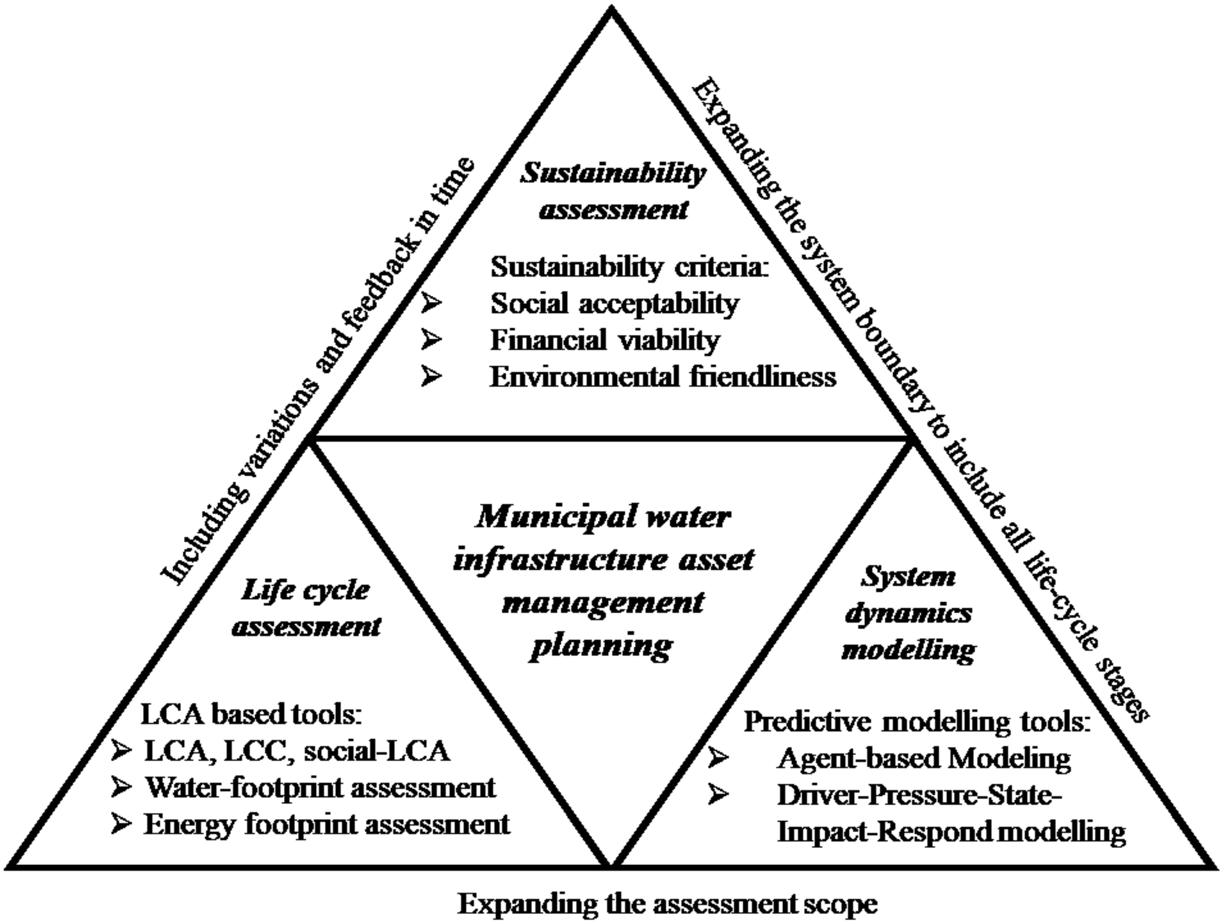


Figure 2-1: Integration of SD and LCA tools.

2.4.2 Conceptual sustainability assessment framework

The conceptual framework proposed for conducting the sustainability assessment of water infrastructure asset management plans has three iterative steps similar to those in ISO-14040 (2006), as presented in Figure 2-2. The sustainability assessment process starts with defining the goal and scope of the assessment and the boundary of the system that will be studied.

The sustainability impacts are measured and presented based on the unit service that is provided to a user ─defined as the functional unit (FU) in the LCA framework in ISO-14040. Various functions and services provided by current infrastructure systems such as distribution of treated water in time and space for drinking, personal hygiene, fire protection, urban recreational aspects; or, collection of wastewater for protection of public health from the spread of diseases, and draining of urban area water for flood control should be considered if an alternative technology or infrastructure system is to be compared with the current infrastructure system (Larsen and Gujer 1997).

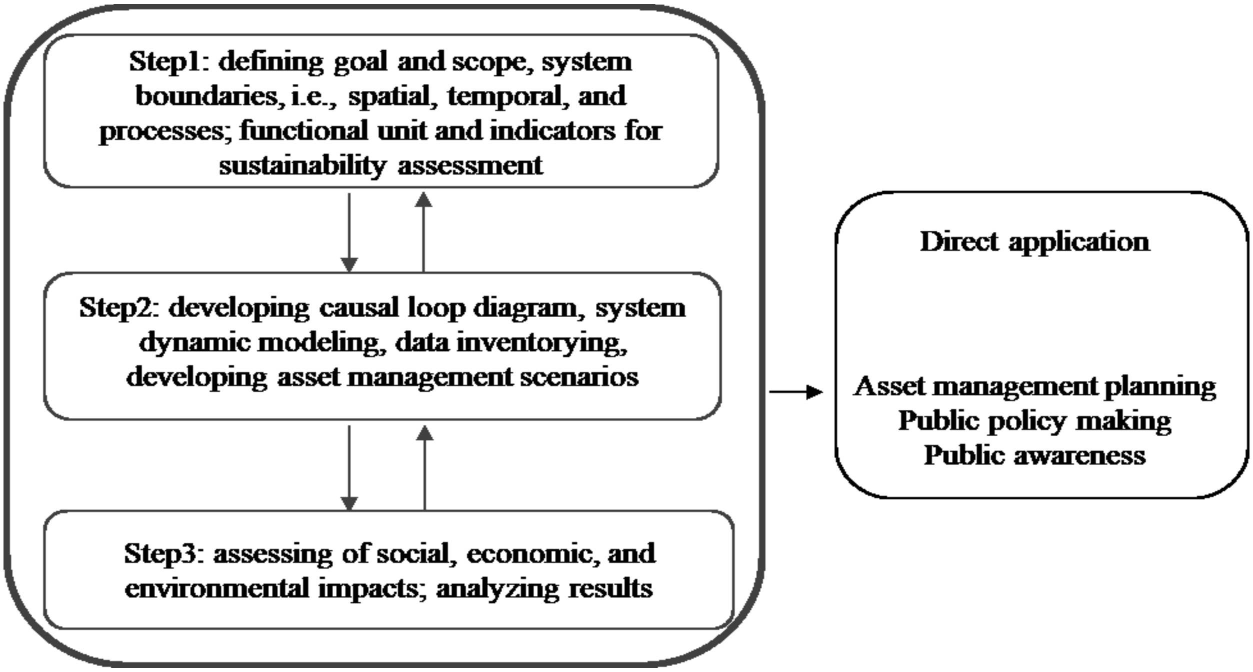


Figure 2-2: Framework for LCSA of water and wastewater assets.

The merit of applying the proposed framework is that it can forecast the long-term trends and responses in complex and dynamic infrastructure systems. Therefore, the goal is to evaluate the sustainability of strategic decisions which overarch several projects within an asset management plan. In this regard, sustainability indicators that parametrize the significant impacts on social, environmental, and economic systems should be selected from the full list of sustainability assessment indicators.

The system boundary demonstrates where the upstream and downstream processes should be cut-off from the assessment. In SD modeling, the system boundary extends to include both the infrastructure system and the affected, as well as affecting cross-boundary systems. The physical system boundary can include the water treatment plants, water distribution and WWC networks, and wastewater treatment plants (WWTP). The temporal boundary needs to take into account the life of the asset that will exhibit the greatest longevity within the system e.g., 100 years to capture the life cycle of the pipes.

The causal loop diagram identifies the interlinkage between different social, economic, and environmental components, and demonstrates the resulting effects of changes on the sustainability indicators. The first step and cognitive mapping process can be conducted with the participation of key stakeholders to elicit the collaboration of water users with analysts in identifying related issues in the sustainability assessment (El Sawah, McLucas, and Ryan 2010). The identified linkages between the related components of social, economic, and environmental systems will be parametrized and quantitatively modeled in the SD model. The initial data that represent the current state of the infrastructure system will be collected and entered in to the model; and the developed asset management scenarios will be simulated.

The third step in the framework is the interpretation of results and conclusion. The quantified material and resource inputs and outputs will be characterized in related social, environmental, or economic impact categories. The results can be multiplied by weighting factors that represent the priority and importance of each social, environmental, or economic impact for decision makers before integrating and comparing the results for different scenarios.

2.5 Demonstration

The proposed framework is applied in a case study of a WWC pipe network system similar to that presented in Rehan, et al. (2014). The following subsections are analogously arranged as the defined steps in the sustainability assessment framework.

2.5.1 Goal and scope of the sustainability assessment

The goal of this demonstrative study is to assess the sustainability of a strategic asset management plan developed for a hypothetical wastewater collection system. The main attributes of the proposed asset management plan are summarized in Table 2-3.

Table 2-3: Scenario attributes.

Asset management plan main attributes	***Value or description***	***Unit***
Finance strategy	Pay as you go	N.A.
Replacement of wastewater collection pipes that have worst internal condition grade (ICG5)*	4.2	km per year
Rehabilitation of ICG4 wastewater collection pipes	4	km per year
Max wastewater collection and treatment fee hike rate	5	% per year

* Based on the UK Water Research Center condition-grade rating system (WRc 2011).

The total volume of emitted greenhouse gases (GHG), the total capital and operational expenses, and the affordability of service use are estimated and monitored as the examples from the full list of environmental, economic and social sustainability indicators, respectively. The selected indicators are presented per FU selected as one-hundred years of connecting and using the wastewater collection and treatment services for a residential user.

The system boundary of the physical asset extends from the WWC pipes network system to the upstream water treatment and distribution, and downstream wastewater treatment, as well as the affected urban road-transportation system. Therefore, the assessment will include the consequent costs on the downstream WWTP system, as well as the GHG emissions from connected and adjacent municipal assets. The time frame of the assessment is 100 years in order to capture the lifecycle of the pipes, as they exhibit the greatest longevity within the infrastructure system (Rehan, et al. 2014).

2.5.2 System dynamics modeling

2.5.2.1 Causal loop diagram (CLD) development

The cause and effect mechanism between the related components of social, economic, and environmental systems is visually described in CLD (Figure 2-3).

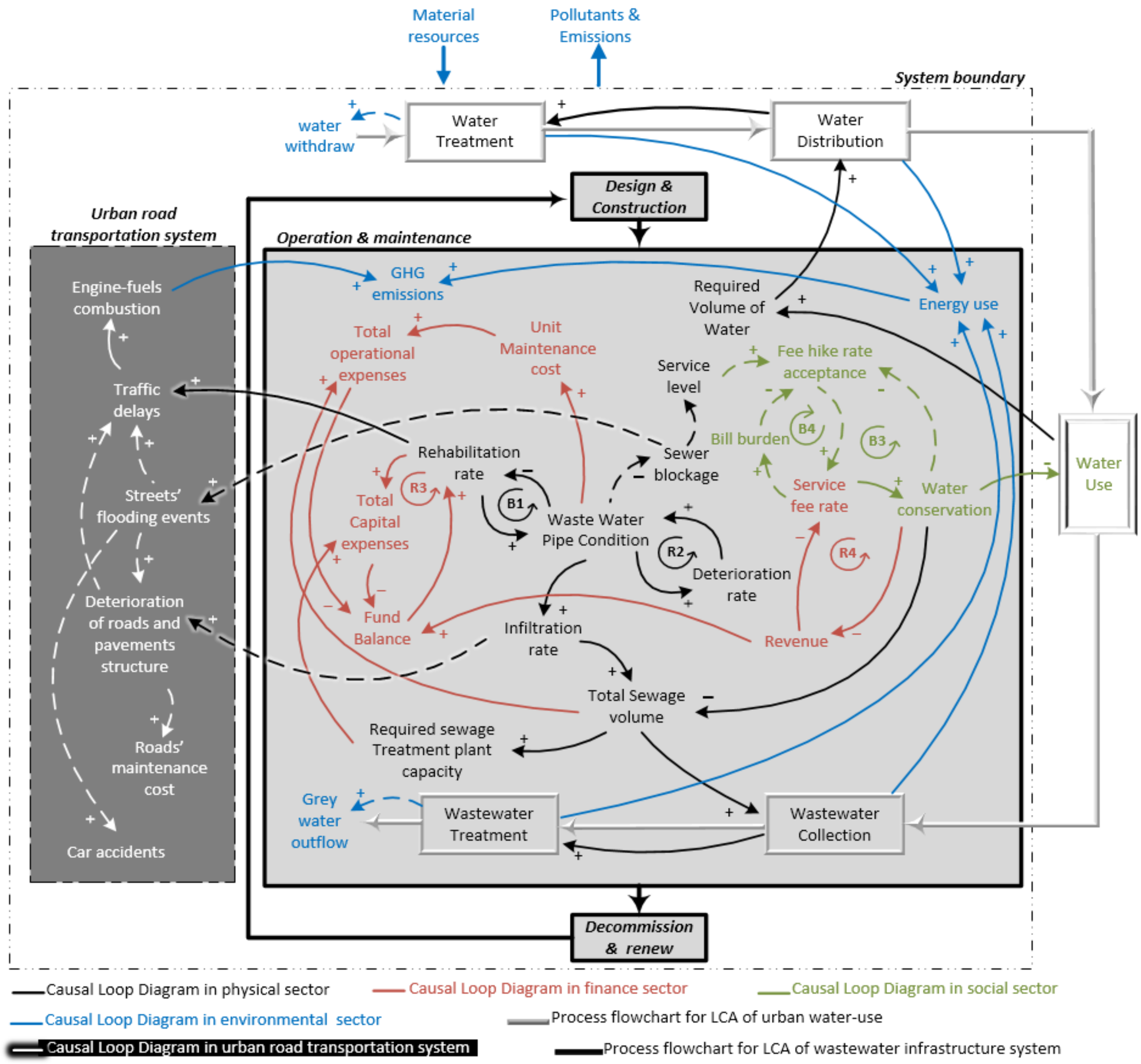


Figure 2-3: Causal loop diagram.

The plus (+) and minus (-) signs on the arrows represent the positive and negative effects on affected components, i.e., a positive/negative sign indicates a similar/opposing change on affected components (Sterman 2000). The letter “R” represents the reinforcing loops, and the letter “B” indicates the balancing loops. Black, red, green, and blue display the cause and effect chain mechanism that exists between the physical, economic, social, and environmental systems, respectively. The dashed lines represent the un-modeled causal relationships in the diagram.

The three main life-cycle stages of the municipal water and wastewater infrastructure system are design and construction, operation and maintenance, and decommissioning and renewal. These life-cycle stages are discerned from the life-cycle stages of the water use (water treatment, distribution, use, wastewater collection and treatment) embedded in the operation & maintenance stage shown in Figure 2-3.

Based on Rehan et al. (2011), the pipes’ deterioration rate increases exponentially as they age. As the pipes age or deteriorate, their internal condition grade (ICG) increases. The increase of the average condition grade of the WWC pipe network will call for greater rehabilitation rates. Rehabilitation of the WWC pipes leads to increasing capital expenses and subsequently a decreasing municipality fund balance. On the urban road transportation side, rehabilitation activities, particularly when done by open-cut trenching technologies, can lead to traffic delays and consequently more GHG emissions (Rehan and Knight 2007).

As the average condition grade of the WWC pipe network increases, a higher volume of ground water infiltrates to the WWC pipe network and subsequently flows into the WWTPs. This results in an increase of the energy footprint of the wastewater collection and treatment systems respectively. WWC pipe defects occur more frequently as the pipes deteriorate, which leads to a rise in the WWC pipe blockage rate and subsequently more street-flooding events. On the other hand, the increase of the inflow and infiltration (I&I) rate results in erosion of the base or subbase supports of urban-road pavements and increases their deterioration rate, which can cause increasing road maintenance costs, traffic delays, or car accidents.

The maintenance and operational costs are also functions of the condition grade of the network. The higher the condition grades, the greater the maintenance cost for the network, and the cost of transportation and treatment of the excessive volume of wastewater. The increased operational and maintenance cost combined with the new policies for financial self-sustainability of the water and wastewater utilities necessitate increased water and wastewater service fees.

The user fee-hike acceptability is a function of affordability (bill-burden) and the service level. As the number of WWC-pipe blockages increases, users are persuaded to pay higher fees to improve the service level by increasing the rehabilitation rate of the network; at the same time, increasing the fees motivates greater water conservation by users. Thus, less water needs to be abstracted, treated, and pumped into the distribution network which in turn reduces the energy-use of the water supply systems.

2.5.2.2 Quantitative modeling

The SD model developed in Rehan et al. (2011) is used as a basis for modelling the sustainability impacts of a WWC pipe asset management plan. Their model is developed further to include the impact of population growth and land development on an urban water system, as strongly requested in Ontario's municipal asset management planning regulations (Ontario Ministry of Infrastructure 2017b). The required wastewater treatment plant capacity and energy-use parameter are also added to their initial model.

As presented in Figure 2-4, the developed SD model in this study consists of four sectors: the consumer, physical, finance, and environment sectors. As in any SD model, this model is constructed with four basic elements: stocks, flows, converters, and connectors. Stock represents the accumulations of physical or non-physical elements in a system, i.e., total available treatment capacity. Flow is used to model the input or output to the stock and represent the activities in a dynamic system, i.e., the wastewater inflow to the WWTP. Converters are used to incorporate the effect of any changing elements in the SD model. Connectors represent the links between convertors, stocks, and flow components.

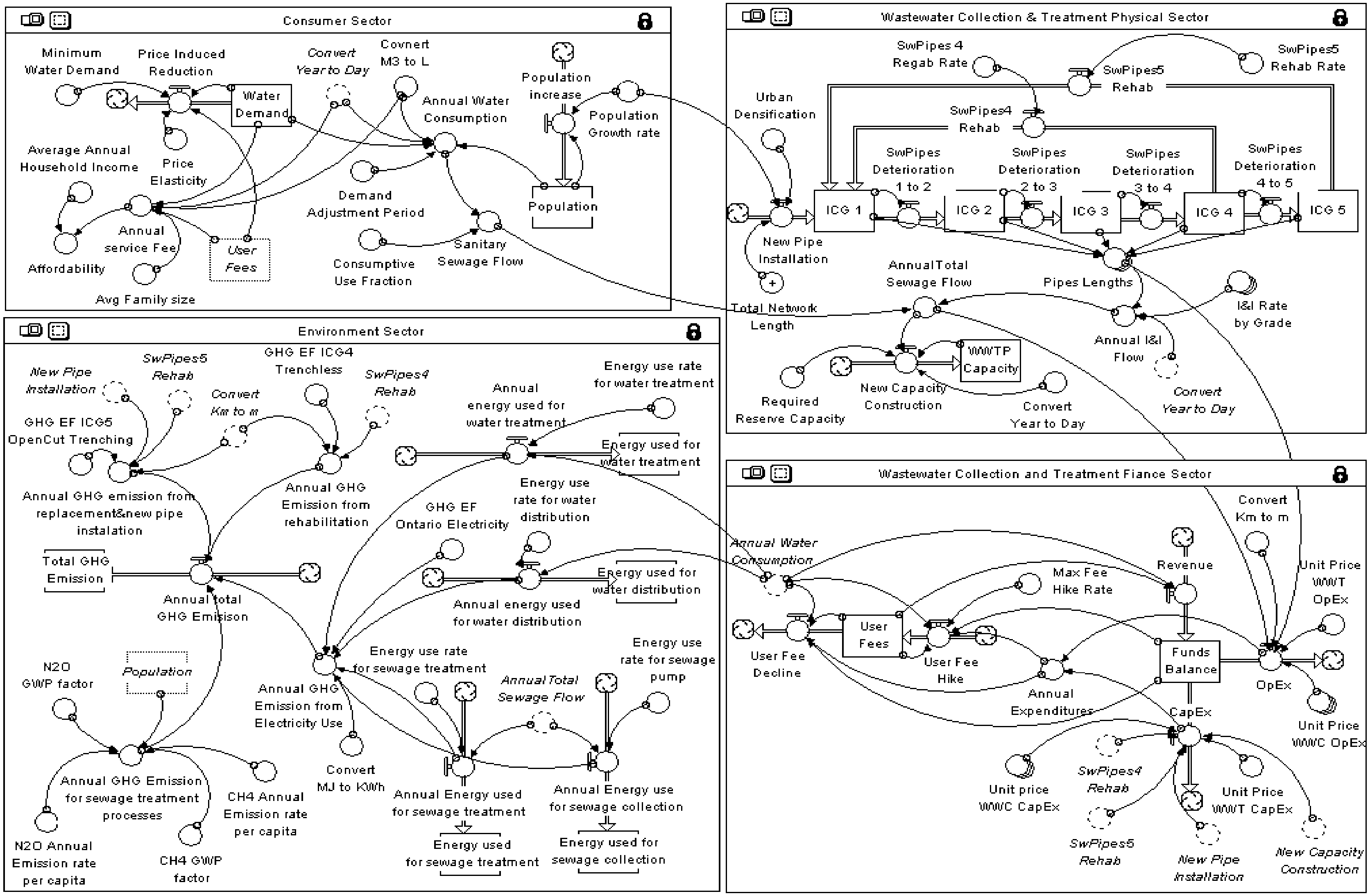


Figure 2-4: SD model of wastewater collection and treatment system.

Mathematically the relationship between stocks and flows can be described using the integral in Equation (2.1), first presented by Sterman (2000).

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow\ (s\ )]ds + \ Stock(t_0) \tag{2.1}$$

where

- $t_0\ [year]$ is the initial time;
- $t\ [year]$ represents the current time;
- $Stock\ (t_0)$ is the initial value of stocks;
- $Inflow\ (s)$ and $outflow(s)$ represent the flow rates into and out of a stock, respectively, at any time s between the t_0 and t, and have the units of $Stocks$ divided by time.

(The parameters and equations used in each part of the model are described in Appendix A.)

2.5.2.2.1 Physical infrastructure sector

The deterioration modeling of the physical infrastructure system is limited to the WWC pipe network system for simplicity and demonstrability. The flow of pipes from the first stock, which represents the new pipes with the best internal condition grade, denoted as $ICG1$ based on the UK Water Research Center rating system (WRc 2011), to the last stock which represents the oldest pipes with the worst internal condition grade or $ICG5$, follows the aged-based deterioration model represented in Rehan et.al., (2014). Two types of pipe rehabilitations are considered in developing asset management scenarios: the $SwPipes5\_Rehab$ which represents the replacement of $ICG5$ pipes with the application of open-cut-trenching techniques, and $SwPipes4\_Rahb$, which represents rehabilitation of the $ICG4$ pipes with application of trenchless technologies. Each of these rehabilitation flows has specific financial and environmental attributes.

The WWTP infrastructure is modeled based on the $WWTP\_Capacity$. As presented in Equation (2.2), the $New\_Capacity\_Construction$ is equal to the sum of the $Sanitary\_Sewage\ Flow$ volume generated by users which depends on the $Population$ and $Annual\_Water\_Consumption$ rate, the $Annual\_I\&I\_Flow$ rate which depends on the

$pipe\_lengths$ in each condition grade, and the $Required\_Reserve\_Capacity$ which is assumed to be equal to the current level of 20% of the annual total wastewater flow.

$$New\_Capacity(t) = (Sanitary\_sewage\_flow(t) + I\&I\_Flow(t)) \times (1 + Required\_Reserve\_Capacity) \times 365 \tag{2.2}$$

where

- t $[year]$ is the current time;
- $New_{Capacity}(t)[m^3/year]$ represents the new wastewater treatment capacity construction in year t;
- $Sanitary\ sewage\ Flow(t)$ $[m^3/year]$ is the volume of wastewater generated by users in year t;
- $Annual\ I\&I\ Flow\ (t)[m^3/year]$ is the volume of inflow of surface water and infiltration of ground water into the WWC pipe network in year t;
- $Required\ Reserve\_Capacity$ [%] represents the extra WWTP capacity required for flash-flooding events;
- 365 $[day/year]$ is used to convert years to days.

The $I\&I\_Rate$ is a function of pipes' internal condition grade. As described in Rehan et al., (2014), the I&I rates for $ICG4$ and $ICG5$ pipes are, respectively, 2.5 and 19 times higher than for $ICG3$ pipe, and the $ICG1$ and $ICG2$ pipes receive no infiltration. 30% of the initial WWTPs' capacity is assumed to be attributed to the initial I&I volume.

2.5.2.2.2 Finance sector

The Finance sector is modeled similar to in the Rehan et al. (2011) model and consists of $Funds\_Balance$ and $User\_Fees$ stocks. The unit costs of $ICG5$ pipe replacement, as well as $New\_Pipe\_Installation$ are set to $\$1000/meter$ (denoted as $Unit\_price\_WWC\_CapEx$). The $Unit\_Price\_WWC\_CapEx$ for $ICG4$ pipe rehabilitation is set to $\$600/meter$. The operational and capital expenses of wastewater collection and treatment are paid from a same funding account, which represent the scenario where the linear WWC pipe network and WWTP systems are owned and managed by one municipal government.

The unit capital expense for WWTP-capacity expansion ($Unit\_Price\_WWT\_CapEx$) is in the range of 2.6 to 3.3 $ million/million liter-per-day treatment capacity adopted from the City of London, Ontario (2015), and the unit operational expenses of the wastewater treatment ($Unit\_Price\_WWT\_OpEx$) is $0.28 per cubic meter.

2.5.2.2.3 Environment sector

The environmental sector model is developed to account for GHG emission which is the indicator of global warming potential (GWP) impacts. A complete set of environmental indicators can be adapted from the LCA tool to account for other environmental impacts, e.g., calculating the water footprint for water pollution and water resource depletion impacts. The GHG emissions are calculated for the following processes:

- On-site GHG emission from wastewater treatment processes ;
- Life-cycle GHG emission for rehabilitation of ICG4 pipes, replacement of ICG5 pipes, and new pipe installation;
- Off-site GHG emission from electrical energy used for wastewater collection;
- GHG emission from electrical energy used for wastewater treatment;
- GHG emission for water treatment and distribution;
- Indirect GHG emission from road-transportation disturbances due to open-cut trenching for ICG5-pipe replacement and new pipe installations, or due to rehabilitation of ICG4 pipes with application of trenchless technologies.

The GHG emissions from manufacturing of materials and construction of wastewater treatment facilities are not included in this calculation as they constitute no more than 5% of the life cycle GHG emissions (Cashman et al. 2014). The emissions from sludge sent to landfill, incinerated, or used over lands are not included in the wastewater and discharge category (IPCC2006).

2.5.2.2.4 Social sector

The social sector model is comprised of $Water\_Demand$ and $Population$ stocks. Water demand is estimated based on the model described in Rehan et al. (2011), and a fixed $Population\_Growth\ Rate$ of 1% is considered for the entire simulation period. Population growth have been developed by integrating a 0 to 100 percent $Urban\_Densification$ index to assess various urban densification scenarios. In the 100% urban densification scenario, new population is served within the current WWC pipe network, which avoids the installation and operation of new pipes. In contrast, the no urban densification scenario will cause the WWC pipe-network length to extend commensurate with the population growth rate, and will incur capital and operational costs for both the WWC and WWTP systems.

2.5.2.3 Data inventories

The initial data used in the Rehan et al. (2011) model have been adopted for this study. For example, the initial length of the WWC pipes distributed in the five condition-grade categories is the same as the initial length of water distribution and WWC pipes in their hypothetical utility. Table 2-4 and Table 2-5 summarizes the initial data inventories for lengths of WWC pipes in each condition grade and the corresponding I&I rates, population, water demand, WWTP capacity and user fees.

Table 2-4: Data inventories of WWC pipes length.

	Internal condition grade (ICG)				
	1	**2**	**3**	**4**	**5**
Length (kilometer)	140	280	140	105	34
Fraction of network (%)	20	40	20	15	5
I&I rate (m^3/km) per day	0	0	4.8	12	91.2

Table 2-5: Initial data entries.

Parameter	***Value***	***Unit***
Population	100,000	capita
Population growth rate	0.1	%
Initial water demand	300	liter per capita per day
Minimum water demand	200	liter per capita per day
Initial wastewater collection and treatment fee	3.75	Canadian dollar/m^3
Initial WWTP capacity	40	million liters per day
Price elasticity of water demand *	-35	%

* Percentage change in water demand per corresponding percentage increase in water service fee

The data-inventory of GHG emissions from different processes that are considered in this is presented in Table 2-6.

Table 2-6: GHG data inventory.

GHG emission ***Considered processes***	$[g\ CO\ eq./m3]$
Drinking water treatment	83*
Water distribution	42*
Wastewater collection	8*
Wastewater treatment	54*
Rehabilitation-replacement	$[kg\ CO\ eq./m]$
Trenchless rehabilitation method of WWC pipes in ICG4 stock	2**
Open-cut installation of new pipes or replacement of ICG5 stock	64**

* based on the energy-use rates reported in Mohammadifardi et al., (2017) and the GHG emission factor for electricity generation reported as 125 [kg CO eq. /kwh] in Sahely et al. (2006).

** Based on the study conducted by Rehan and Knight (2007) and assuming an average daily traffic of 3,500 vehicles per year.

According to IPCC (2006) protocol, the on-site methane gas ($CH4$) emission from wastewater treatment is considered to be zero (by assuming that all treatment plants apply a well-managed aerobic treatment method). The nitrous oxide ($N2O$) emissions from treatment processes–if industrial and commercial discharges are attributed to residential users–is considered to be 4 grams per person per annum (IPCC 2006).

The GWP factor of nitrous oxide gases ($N2O\_GWP\_factor$), which represents the relative potency of N_2O gas compared to an equivalent mass of CO_2 gas, is considered to be 296 (US-EPA 2018).

2.5.2.4 Scenario development

Alternative scenarios for urban area development are tested in the sustainability assessment of the proposed asset management plan. The two extreme conditions─100% urban densification and 0% urban densification─are compared with 50% densification, the most probable scenario. In addition, the third scenario is repeated with a zero population growth rate condition to evaluate the impact of population growth on the results. The conditions in each scenario are summarized in Table 2-7.

Table 2-7: Alternative scenarios with respect to urban densification policy.

Scenario ***Conditions***	***0% densification***	***50% densification***	***100% densification***	***No population growth***
ICG5 replacement (km/year)	4.2	4.2	4.2	4.2
ICG4 rehabilitation (km/year)	5	5	5	5
Urban densification (%)	0	50	100	0
Population growth (%)	0	0.1	0.1	0
Max user-fee hike rate (%/ year)	5	5	5	5

2.5.3 Interpretation of results

The simulation results are presented in Figure 2-5, Figure 2-6, Figure 2-7, and Figure 2-8. The average condition grade of the WWC pipe network, as presented in Figure 2-5, plot (a), is decreasing for all scenarios until the year 80, when it slightly increases for the 50% densification and no-population-growth scenarios. The average condition grade decreases at the highest rate in no-densification scenario, as the WWC pipe network is expanding with new pipe installations at the highest rate (Figure 2-5, plot (b)).

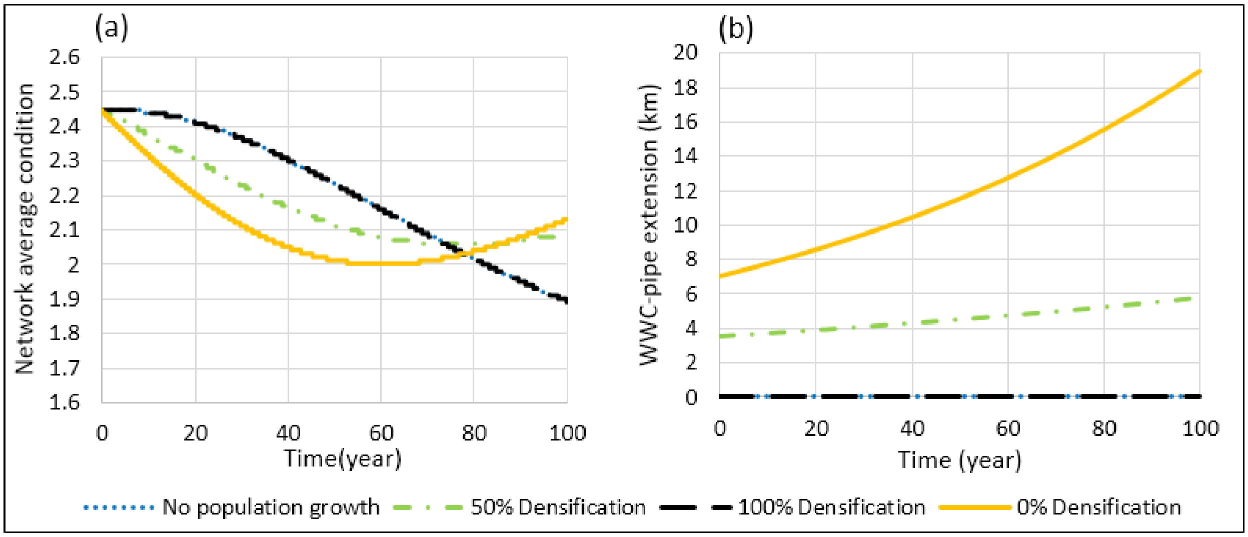


Figure 2-5: a) WWC network average condition and b) WWC network extension results.

As it is shown in Plots (a) and (b) of Figure 2-5 and Figure 2-6, the physical sector behaves similarly in the no-population-growth and 100% densification scenarios. The urban area development and accordingly the network expansion will be null when the population growth is zero, which is a similar condition to 100% urban densification.

The annual infiltration volumes in all scenarios is presented in Plot (a) of Figure 2-6. It shows that less urban densification will result in a higher I&I volume. The fraction of ICG 5 pipes is presented in Plot (b) of Figure 2-6. Only in the 50% densification scenario, which is the most probable future plan for urban area development, is the percentage of ICG 5 pipes below 10% during the entire life cycle of the WWC pipe network system. In no-population growth and 100% densification scenarios, the fraction of ICG 5 goes above the 10% threshold after the first 20 years; but in the no-densification scenario, it surpasses the 10% threshold near the end of the simulation period.

Plot (c) in the previous figure shows the corresponding new WWTP capacity that needs to be constructed for extraneous wastewater flow. Although the I&I rate is decreasing in the 100% densification scenario, the increase in the generated sewage volume from population growth will compel building additional treatment-plant capacity. Unlike the 100% densification scenario, no more treatment plant capacity is the required in no-population growth scenario after the I&I starts to reduce in year 40.

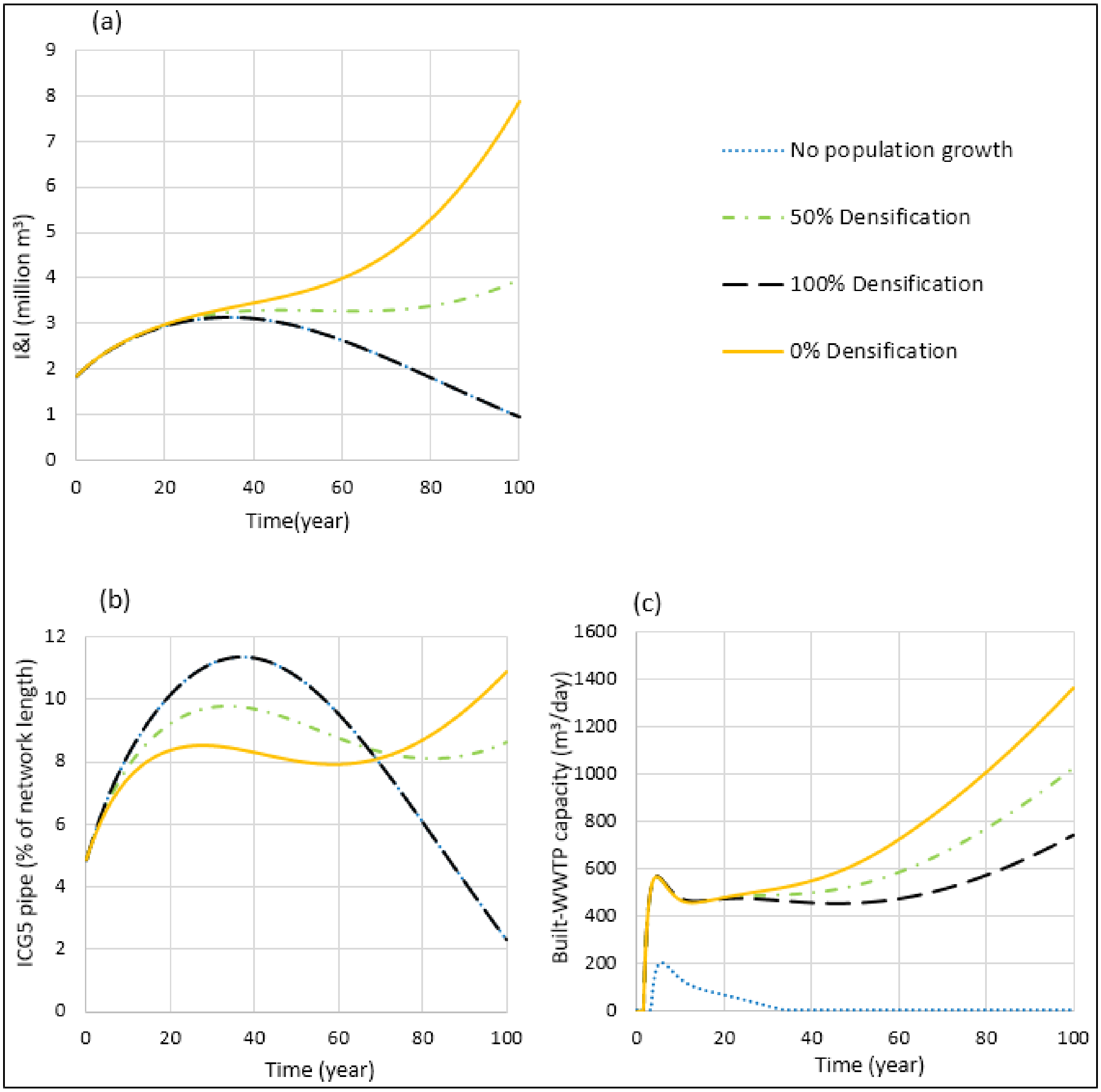


Figure 2-6: a) Annual I&I, b) Fraction of ICG5 pipe and c) Built WWTP capacity results.

The affordability or bill burden results, presented in Plot (a) of Figure 2-7, correspond to the user-fee resutls presented in Plot (b) of Figure 2-8: the most-affordable service result from the 100% urban densification scenario, and the lease affordable service result from the 0% urban densification scenario.

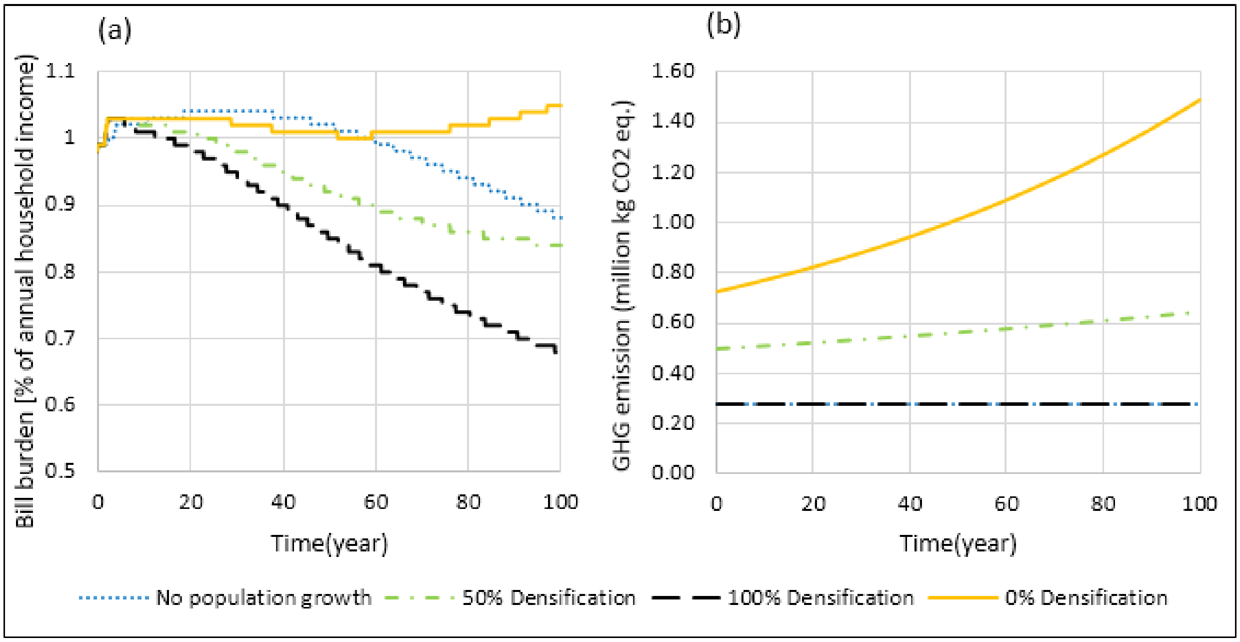


Figure 2-7: a) Bill burden and b) GHG emissions results.

The Plot (b) of Figure 2-7 demonstrate the annual total GHG emissions in each scenario. The GHG emission results show a significant difference between the 0% densification and other three scenarios. The annual total GHG emission increases at its highest rate and reaches approximately 1.5 million kg CO_2 eq. per year in the no-densification scenario, which is about 2.5 times higher than that for the 50% densificaiotn scenario, and 5 times higher than those for the two other scenarios.

The annual expenses for wastewater collection and treatment, user fees, and annual water demand are presented in Plot (a), (b), and (c) of Figure 2-8, respectively. The total operational and capital expenses of wastewater collection and treatment increases for all scenarios except the no-population growth scenario (Plot a). In the other three scnearios, the operational expenses for wastewater collection and treatment increase as a result of population and sewage-generation growth. The 100% urban densification scenario results in the smallest user-fee projections among all scenarios. Although the total annual expenses in the no-population growth scenario are lower than those in the 50% densifcation scenario, the share of the users from total expenses is higher. In fact, the user-fee in this scenario is the highest among all scenarios for the first 60 years. After year 60, the user fee in the 0% densification scenario starts to increase and surpasses the user fee in the no-population growth scenario, to reach to nearly 2.9 \$/ m^3 at the end of the simulation period. The highest user fee increases will result in water demand reduction to relatively the lowest level in all scenarios, which is 284 liter-per-capita-per-day at the end of the simulation period.

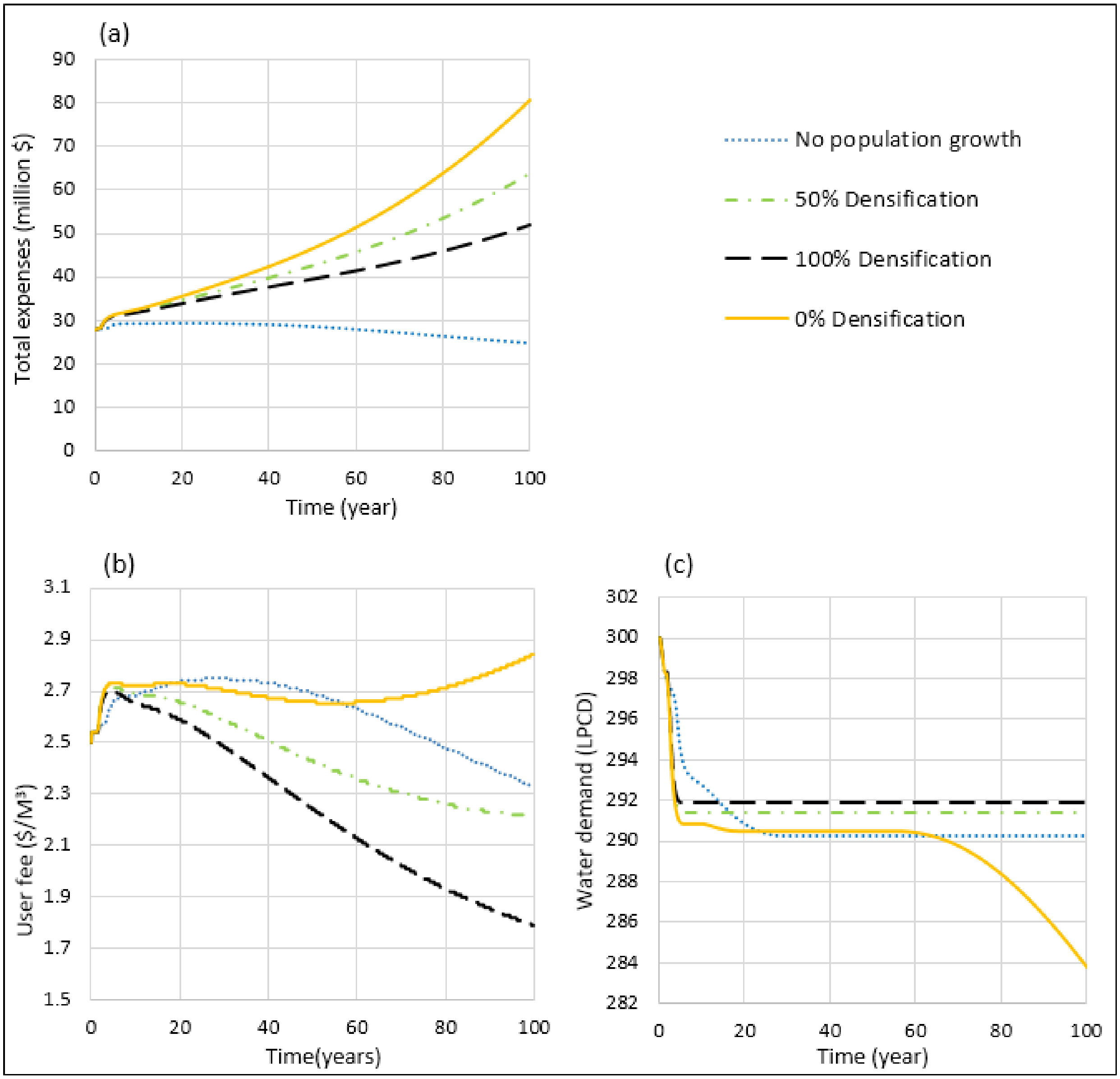


Figure 2-8: a) Total expenses, b) User fee and c) Water demand results.

These results are selectively presented to demonstrate the utility of the proposed framework. A more-complete list of indicators, as presented in Ganjidoost et al. (2018) or

Sahely, Kennedy, and Adams (2005), will be needed to conduct a practical sustainability assessment for the proposed scenarios.

2.6 Summary and conclusions

The sustainability assessment framework is proposed to assess the sustainability outlook of various strategic decisions for asset management of water and wastewater infrastructure systems. This tool is also applicable for other types of municipal assets, such as road transportation infrastructure, telecommunication infrastructure, and public buildings.

The most important aspects of the framework are that

- It encompasses system wide analysis and includes the whole life cycle of the system;
- It deals with non-linearity, variations and dynamic features of the systems;
- It supports scenario development and assessment of different asset management plans;
- It has the capability of integrating different perspectives and interacting with stakeholders in the early phase of modeling and identifying the causal and effect chain mechanisms;
- Finally, it includes integrated assessment of all sustainability dimensions as social, environmental, and economic sustainability.

Application of the proposed framework will enable asset management planners to foresee undesired consequences of their current strategic decisions on social, economic, and environmental systems.

Chapter 3

Development of an asset management planning tool for integrated wastewater collection and treatment systems

Abstract

In many Canadian municipalities, wastewater collection (WWC), and wastewater treatment plants (WWTP) are owned and managed by separate levels of hierarchical municipal governments. Linear water and WWC pipe networks are owned and managed by utilities at the lower tier of municipal government, and vertical treatment plant assets are owned and managed by regional governments at the higher tier. Under this arrangement, regions charge utilities for treating water and wastewater. As these two assets are directly linked to one another, changes to the operational condition of one system impact the operational condition of the other. Securing funding for capital and operational expenses of WWTPs has the same, if not a higher priority if sustainable wastewater infrastructure systems are to be achieved.

This chapter presents the development of a system dynamics model for better understanding the interrelation and feedback mechanism between the WWC pipe network and WWTP systems. A causal loop diagram is constructed to present the links between WWC pipe network and WWTP systems and to depict the feedback mechanisms existing between physical, financial, and consumer sectors. Then, the presented cause-effect chains are mathematically parametrized and modeled in the novel system dynamics model.

Application of this model will enable decision-makers to assess the sustainability impacts of their strategic decisions on wastewater collection and treatment systems, find synergistic cost-saving opportunities, and improve the sustainability performance of their asset management plans.

Key words: System dynamics modeling, wastewater treatment plant, wastewater system

3.1 Introduction

System dynamics (SD) has often been applied as a convenient simulation tool for modeling the socio-economic impacts of strategic decisions on water resource management problems (Mirchi et al. 2012). In WWTP systems, SD modeling is been used as an optimization technique for designing WWTP systems. Das et. al., (1995) and Gillot et al. (1999) modeled the dynamics and complexity of wastewater treatment operation and presented the feedback mechanisms exist between different wastewater treatment processes and components.

Recently, SD tool has been used to model the complexity of water and wastewater infrastructure systems. Chung et al., (2008) applied the SD tool to model water sources, users, recharge facilities, and water and wastewater treatment plants (WWTP) as subsystems for general water supply planning, and to calculate the construction, operation and maintenance costs of water and WWTPs. Biachia and Montemaggiore (2008) integrated SD with the "balanced scorecard" approach to analyze the dynamics and interdependencies between key financial indicators and intangible variables such as the customer satisfaction, business image, and bargaining power of a water utility company.

Ganjidoost (2016) developed a framework that models the feedback mechanism of integrated water distribution and wastewater collection (WWC) network systems, using the SD modeling approach. He has shown how upstream water distribution systems affect wastewater collection systems based on the extraneous infiltration from leaky water distribution pipes. His model has been built on Rehan et al., who 1) in 2013, applied the SD tool to model urban water distribution systems, and 2) in 2014, developed an SD model to evaluate the financial sustainability of urban WWC systems. Various interconnections and feedback between the physical, financial, and social systems related to the linear water and wastewater infrastructure were modeled in their research.

Previous SD models have only considered the linear water and/or wastewater network system (s), leaving the cost of wastewater treatment as an exogenous factor. A complete model of an integrated water and wastewater infrastructure system should include both the linear water distribution and WWC networks and the non-linear water and wastewater treatment systems, as illustrated in Figure 3-1.

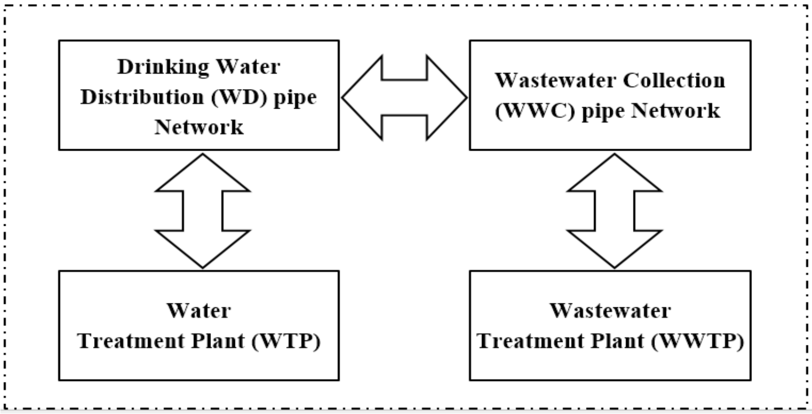


Figure 3-1: A complete water and wastewater infrastructure system.

While the revenue of the WWTP sector is generated based on consumers' metered water, its operational expenses are based on the fraction of metered water plus the extraneous inflow and infiltration (I&I). Rehan, et al. (2014) showed that the I&I makes a significant contribution to wastewater volume; on average, the monthly volume of collected wastewater is 25% higher than the corresponding volume of metered water, and at peak-flow exceeds it by 74% (Rehan, et al. 2014).

This present study is the first attempt to model integrated wastewater collection and treatment systems at the strategic level. The conceptual and simple SD model presented in Chapter 2 is next developed into an advanced model that has been parametrized with data collected from several small to medium size municipalities in southern Ontario. First, a novel SD model for simulating WWTPs' physical and financial performance is developed and integrated into the WWC asset management planning model. Second, an energy footprint and greenhouse gas (GHG) emission modules, as a proxies for the environmental sector, are developed and added to demonstrate the application of the SD model for environmental sustainability assessment. Moreover, the Ganjidoost et al. (2015) physical, social, and finance sectors of the WWC asset management planning model are revised and updated to account for the effect of population and urban area development.

The system dynamics of urban water and wastewater system and its importance for complete sustainability assessment are not considered in current approaches (Upadhyaya 2013). The present SD model is developed as part of the sustainability assessment framework introduced in the previous chapter. Application of this model within the sustainability assessment framework will enable to project the sustainability impacts of strategic decisions on wastewater collection and treatment systems.

3.2 Causal-loop-diagram development

This section explores the interactions and feedback between WWC and WWTP systems and presents the developed modules for SD modeling of different related sectors such as the joint consumer sector, separate physical as well as financial sectors for WWC and WWTP systems, and joint environmental sectors.

The total inflow volume received by a WWTP depends on the volume of inflow and infiltration (I&I) entering into the WWC pipe network system, and the volume of sewage generated by system users. The infiltration rate to the WWC pipe network system increases as WWC pipes deteriorate and their internal condition grade increases. Sewage generation is increased by population growth, which also affects the I&I flow rate due to WWC pipe network expansion in urban area development. The consequence of an increasing inflow volume is an increasing cost of operating WWTPs, and the need for capital investment to expand capacity. In contrast, it is assumed that decommissioning a WWTP will have no significant capital cost. Construction and operation of new WWTP capacities, as well as the installation and operation of extended WWC pipe network will increase the energy footprint of the whole system.

To increase the fund balance, utilities need to increase revenues by increasing user fees. As wastewater collection and treatment fees are directly tied to the metered volume of water, the response of users will be water-demand reduction, leading to a decrease of the energy footprint by reducing the energy-use in upstream water treatment and water distribution systems. Population growth will also increase the user-fee based revenues of WWC and WWT utilities. Development charges are another revenue stream for utilities, collected to cover the required capital work expenses due to urban development.

Qualitative relationships among the variables below are identified in a causal loop diagram (CLD), then parametrized in the SD model. Figure 3-2 presents the CLD for the SD model for WWC and WWTP systems.

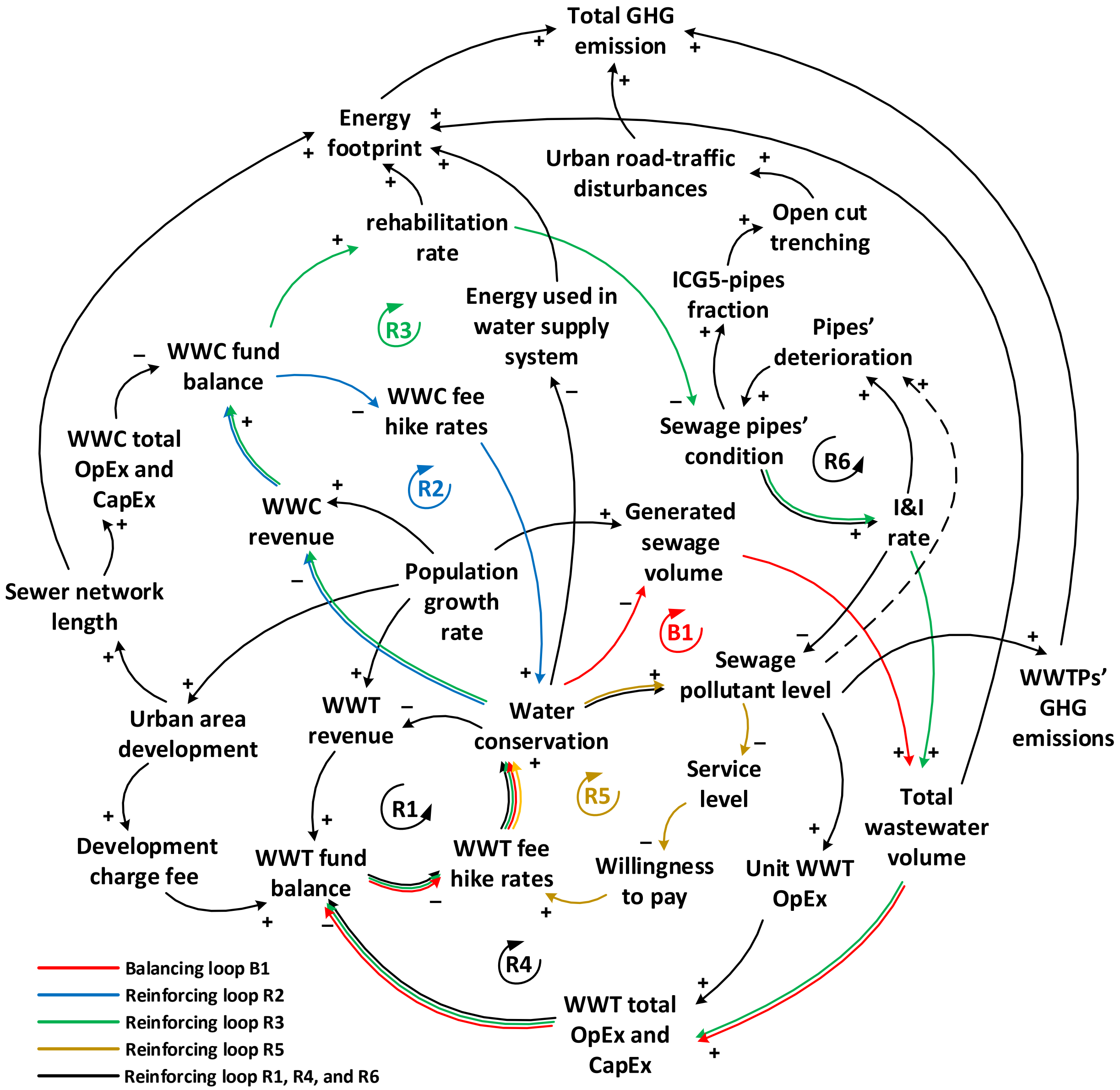


Figure 3-2: CLD model of wastewater treatment plant system.

A plus (+) or minus (-) sign is used to represent the positive or negative influence of a variable. A positive link indicates that a positive/negative change in one parameter will cause a similar subsequent positive/negative change in the linked parameter. In contrast, a negative link indicates that the linked variables are conversely related to each other, so that a positive/negative change in one variable will result in a negative/positive change in the dependent variable. Two feedback loops are identified in the CLD: the reinforcing loops, which represent positive feedback, shown by “R”, and the counteractive balancing loops, shown by “B”.

The reinforcing loops (R1) and (R2) show that users’ water-conservation efforts result in decreasing revenues and less available funds for utilities. Reinforcing loop (R3) shows that the increasing WWT fee reduces the funds available for reinvestment and rehabilitation of the WWC pipes, which in turn, leads to further deterioration of a WWC pipes, or increasing their condition, and increasing I&I flowing into WWTPs.

Reinforcing loop (R4) shows the cause-and-effect-chain mechanism that exists between water conservation, sewage pollutant levels, operation and maintenance costs of the WWTP systems, fund balances, and fee hikes. Water conservation, as well as I&I reduction will increase pollutant concentrations in wastewater. Marleni et al. (2015) have demonstrated that the water-use reduction in various water-demand management scenarios increases the concentration of sulphide and sulphate levels by 30% and 40% respectively. These two compounds, which are the main source of hydrogen sulphide formation, will cause odor problems and corrosion of WWC pipes. This result is shown by a dashed line to imply that the causal link is not implemented in the model.

(R5) shows that increased pollutant concentration, from water conservation, will increase WWC pipes’ blockages and odor problems, resulting in reduced service performance of the wastewater pipe network. The increase of WWC pipes’ blockages and odor problems will increase the willingness of service users to accept fee hikes and pay for service improvements.

Parkinson et. al., (2005) have reported that an increase in the concentration of suspended solids (SS) and biological oxygen demand (BOD) in wastewater are a result of water-conservation scenarios. Min and Yeats (2011) have shown an increase in the operational cost of WWC and WWT services as a result of BOD and SS level increases. The increased BOD level will increase the methane gas yield as a main source of GHG emission from wastewater treatment processes (IPCC 2006).

DeZellar and Maier (1980) argued that the total cost of wastewater treatment might be lower with a decrease of the total wastewater volume, but the unit cost of the operation and maintenance of WWTP increases due to non-routine operational problems such as clogging, changing bacterial activities or malfunctioning of the biological treatment processes, and the extra chlorination and recirculation needed to prevent odor problems, etc.

Reinforcing loop (R6) shows the acceleration of pipe deterioration rates when increasing the I&I flow rate worsens the pipes' condition. The balancing loop (B1) shows that the reduction of total wastewater volume from water conservation will lower the operational and capital expenses and help to increase the fund balance. The increase of the fund balance will reduce the service-fee-increase rate, leading to a decline in water conservation practices by consumers.

3.3 SD Model development

The SD model is developed using Stella® software, Research Version 9.1.4 (Richmond 1997).The four basic elements, as in any SD model, are the stock, flow, converter, and connector, depicted in Figure 3-3.

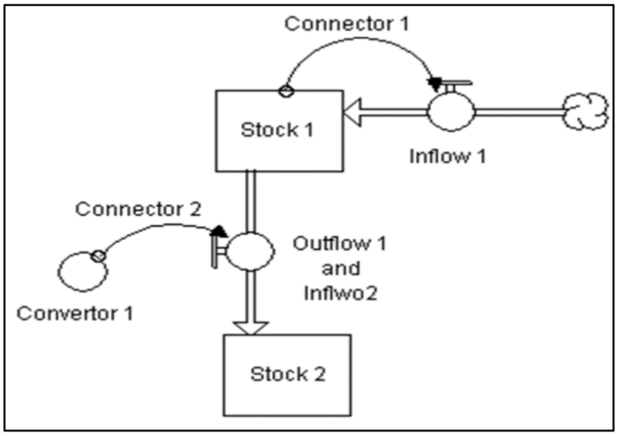


Figure 3-3: Main components of a system dynamics model.

"Stocks" represent the accumulation of physical or non-physical elements in a system, i.e., the total available treatment capacity. "Flows" are used to model the inputs or outputs to the stock, and represent the activities in a system, i.e., the wastewater inflow to the treatment plant.

“Converters” are used to incorporate the effects of changing variables in an SD model. “Connectors” represent the links between the convertors, stocks, and flow components of an SD model. Mathematically the relationship between stocks and flows can be described using Equation (3.1) (Sterman 2000).

$$Stock\ 1\ (t) = \int_{t_0}^{t} [Inflow\ 1(s) - Outflow\ 1(s)]ds + Stock\ 1(t_0) \tag{3.1}$$

where

- t_0 is the initial time;
- t is the current time;
- $Stock\ 1\ (t_0)$ represents the initial value of the stock 1 shown in Figure 3-3;
- $Inflow\ 1\ (s)$ and $outflow\ 1(s)$ are the flow rate into and out of a stock 1 respectively (Figure 3-3) at any time s between the t_0 and t, and have the units as $Stock\ 1$ divided by $time$.

3.3.1 Consumer sector

Consumers reactions to incremental change of wastewater service fees are modeled based on Rehan (2011) model. The daily water-use per capita or water demand is estimated as a function of the $Price\ \_Elasticity$ $[-]$ of demand, $User\_Fee$ $[\$/m^3]$, and $Minimum\_Water\_Demand$ $[liter/capita/day]$ (Figure 3-4).

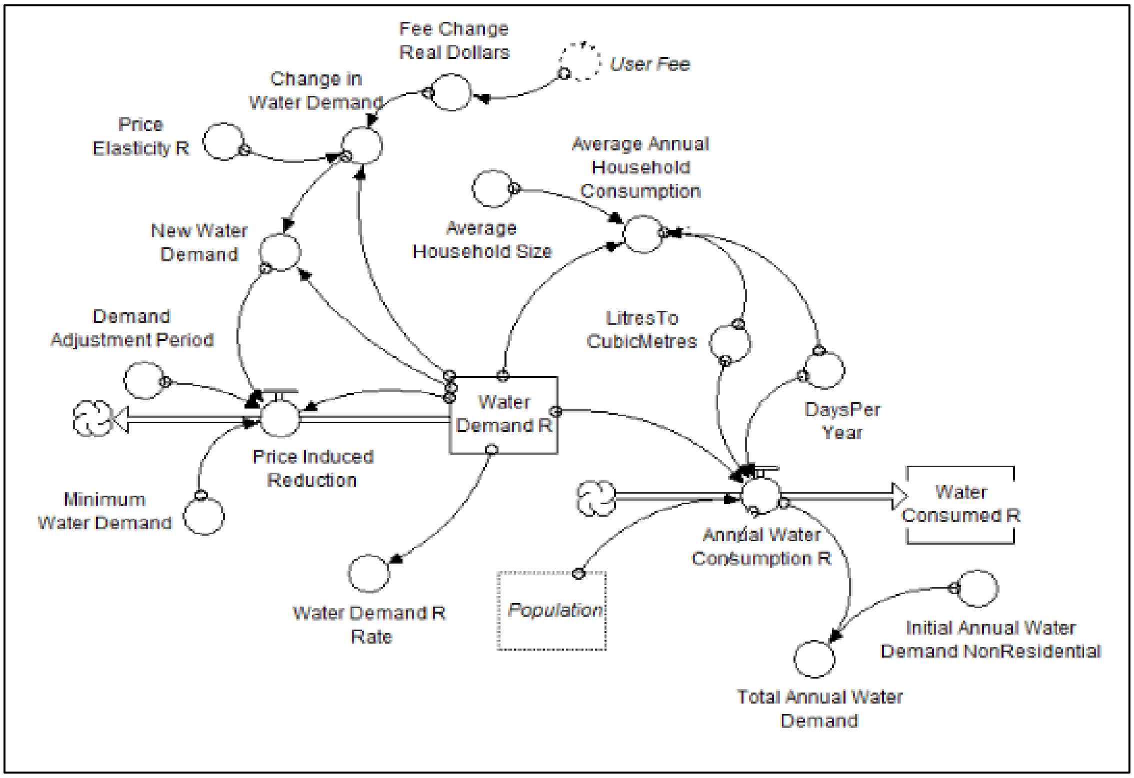


Figure 3-4: Consumer water demand change.

The price elasticity of demand, which is the percentage change in water demand per corresponding percentage change in the fee, is selected as - 0.35, similar to the Rehan et al. (2015) SD model. The minimum water demand is considered to be 150 liters per capita per day (LPCD) and follows from Ganjidoost (2016).

In this study, the modeling of the consumer sector is improved by decoupling non-residential and residential users, as well as by developing the population growth model. In Ganjidoost (2016) model, water demand is calculated as the sum of residential, commercial, institutional and industrial water demand divided by population, under the assumption that all customers experience the same price elasticity of water demand. However, this assumption does not address that the industrial users can often apply technological means to reuse and conserve water and significantly cut their water demands. Water and wastewater utilities also set different price rates for non-residential users, in consideration of their social and economic importance to the societies who are depending on them. The water demands, wastewater collection and treatment fees for non-residential users are assumed to be fixed in the present model.

The new model better represents the projection of user-fee based revenues, user-fee hike rates, and the wastewater volume collected and treated in the WWC and WWT models. A policy favoring fixed wastewater service fees for non-residential users indicates a strategy whereby residential users are subsidizing the system, and the result is a more stable economic sector. The wastewater collection and treatment services are subsidized for commercial, institutional, and industrial users if their fee increase rate is lower than the residential fee-hike rates and vice versa.

Population growth has been modeled by an urban densification index (UDI) to represent various urban development scenarios. In 100% urban densification ($UDI = 1$), new population is served within the current WWC pipe network which avoids the need to install and operate new pipes. It also does not impact the WWTP system's operation and capacity planning due to future I&I to the new parts of the WWC pipe network. In contrast, a no urban densification scenario ($UDI = 0$) requires a growing WWC pipe network which would incur capital and operational costs for both the WWC and WWTP utilities. The impacts of urban densification on the WWTP-finance sector and environmental sector are described in Section 3.3.3 and Section 3.3.4, respectively.

3.3.2 Physical infrastructure sector

This section provides a brief overview of the WWC pipe network SD model developed by (Rehan 2011), followed by the new model development for the WWTP system.

3.3.2.1 WWC pipe network physical model

Pipe inventories are made up of different pipe materials such as vitrified clay, concrete, polyvinyl chloride (PVC), ductile iron, etc., and are grouped into five classes, which are represented in Figure 3-5 as stocks, based on their internal condition grade (ICG) as defined by the Water Research Center in the United Kingdom (WRc 2011). The method used in Rehan et al. (2014) is adapted to define the deterioration and infiltration rates.

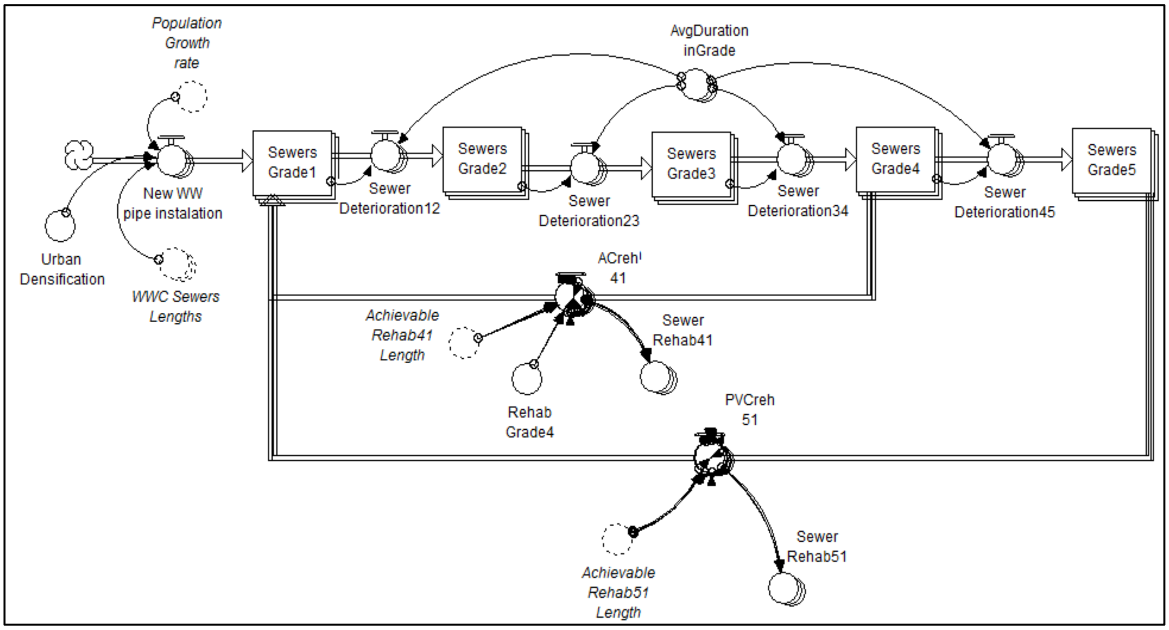


Figure 3-5: The WWC pipe network model.

New pipes with the best ICG are in the first stock class, whereas pipes in the worst condition belong to the fifth stock class. Today, PVC pipes are used in new pipe installation projects. Therefore, the new pipes, either for upgrading the ICG5 stock or for urban development and network expansion, are entered into the first PVC pipe stock.

3.3.2.2 Wastewater treatment-plant physical model

The physical assets of WWTPs consist of electromechanical equipment, such as pumps, motors, aerators, mixers, tanks, basins, pipes, and buildings. Figure 3-6 shows the modeling of WWTP assets at a strategic level, which is based on the WWTP capacity requirement.

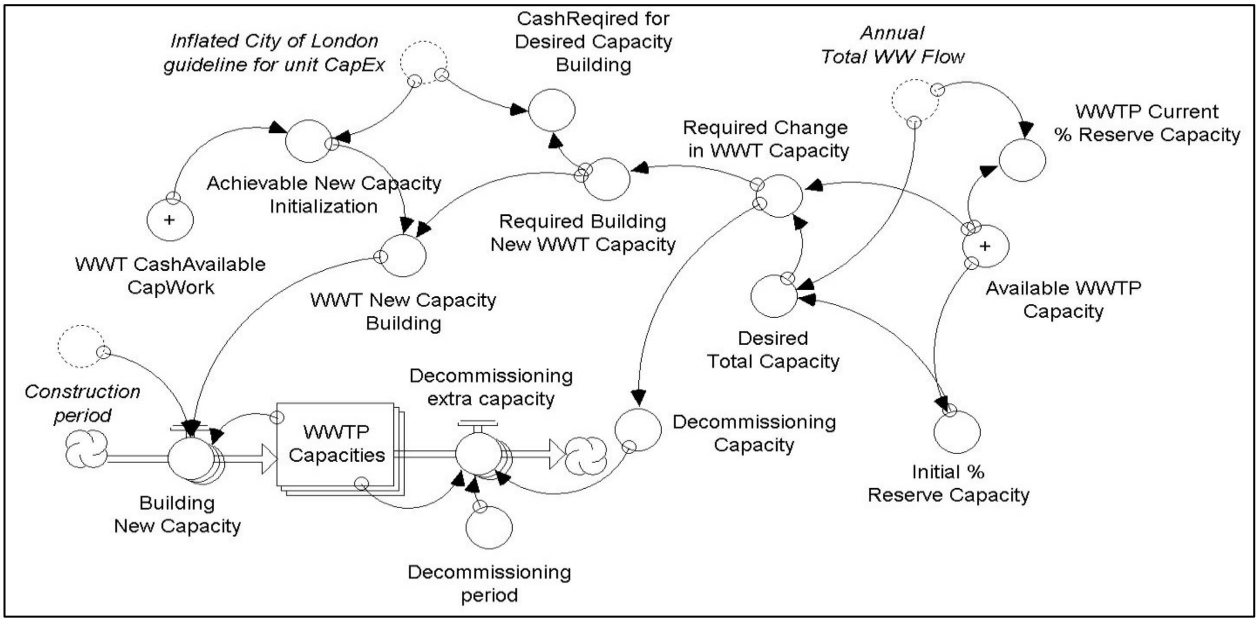


Figure 3-6: WWTP capacity model.

The $Required\_Change\_in\_WWT\_Capacity$ $[m^3/d]$ is equal with the difference between the $Available\_WWTP\_Capacity$ $[m^3/d]$ and the $Desired\_Total\_Capacity$ $[m^3/d]$, which is the sum of annual total wastewater flow ($Annual\_Total\_WW\_Flow[m^3/d]$) and the required reserve capacity ($Initial\_\%\_Reserve\_Capacity$ $[m^3/d]$).

The reserved capacity for the maximum seasonal, daily, and hourly peak wastewater flow can be estimated based on two methods: 1) the current reserve capacity of the WWTPs, or 2) based on the recommended standard defined by the Great Lakes-Upper Mississippi River Board (2014). The desired reserve capacity in this model is calculated based on the initial percentage reserve capacity percentage, which is assumed to be maintained for the entire simulation period.

A positive difference indicates that capacity construction must be initiated ($Required\_Building\_WWT\_Capacity$ $[m^3/d]$) whereas a negative difference suggests the decommissioning of extra capacities. The annual total WW flow is estimated based on the sewage generation from residential and non-residential users and the annual I&I flow. The sewage generation rate depends on the population growth rate and water demand rates, and the I&I flow rate depends on the WWC pipes' conditions.

3.3.2.3 I&I calculation model

The initial annual I&I volume is used as the basis for estimating the future I&I rate. The initial I&I volume equals the sum of initial infiltration and initial inflow volumes.

The initial infiltration volume is derived by subtracting of the base sanitary flow (BSF) from the annual average wastewater flow. The BSF volume can be calculated by one of the two methods recommended by the U.S. Environmental Protection Agency (EPA) (2014).

In the first method, the BSF is derived by subtracting the average minimum wastewater flow recorded at the WWTP during a dry weather period (7 to 14 days before the rainy season starts and when the ground water level is high) from the average wastewater volume for the same period of the reported year.

In the second method, the BSF is calculated by subtracting the average volume of consumed water from the average volume of metered water (for a period of time before outdoor recreational activities start). The consumed water represents the amount of metered water that has not been discharged to the WWC pipe network after use.

The inflow volume can be estimated by subtracting the BSF and infiltration volumes from the WWTP inflow volume for the days with reported precipitation.

3.3.2.4 Wastewater composition model

The concentration of SS and BOD is assumed to increase proportionally with declining wastewater volume flowing into WWTPs. The unit mass of BOD and SS per capita is assumed to be fixed in time and is calculated based on the annual mass of BOD and SS reported by the WWTP divided by the current population. Thus, the concentration of SS and BOD changes as the generated wastewater ─which is a function of the water demand (WD) and the consumptive use fraction (CUF) of metered water─ and $I\&I$ change over the simulation period. The BOD and SS models are presented in Figure 3-7, and their concentration are formulated as in Equations (3.2) and (3.3) respectively.

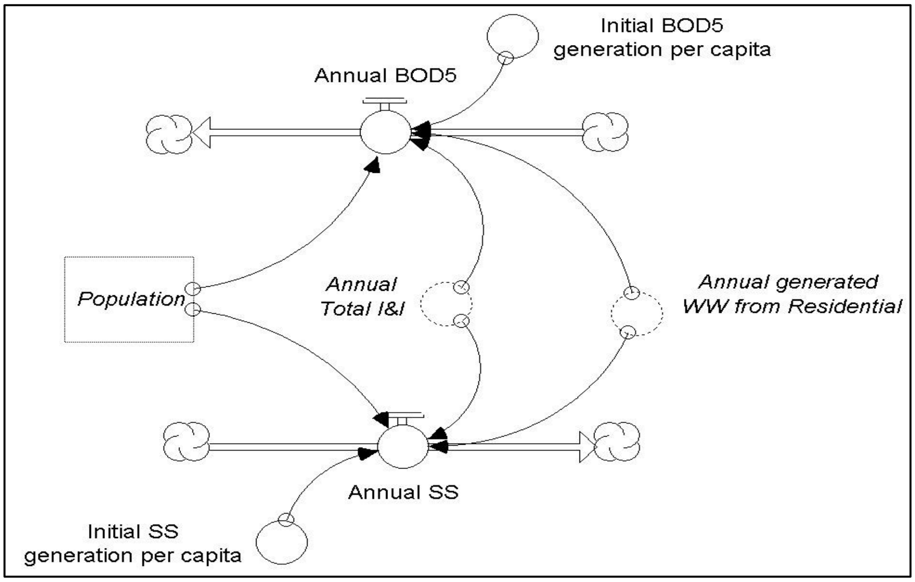


Figure 3-7: BOD and SS concentration change model.

$$SS\,(t) = \frac{(\boldsymbol{SS_0})\times population(t\,)}{\frac{365}{1000}\times WD(t)\times(1-CUF)\times popuation\,(t)+I\&I\,(t)} \tag{3-2}$$

where

- $t\,[year]$ is the current time;
- $SS(t)\,[g/l]$ is the concentration of suspended solid in wastewater inflow at WWTP in year t;
- $SS_0\,[kg/capita/year]$ is the initial mass of suspended solid generation per capita;
- $\frac{365}{1000}\,[(\frac{day}{year})/(\frac{m^3}{liter})\,]$ is the conversion factor to convert days to year and liter to cubic meter;
- $WD(t)\,[liter/capita/day]$ is the average daily water demand of a residential user in year t;
- $CUF\,[\%]$ is the percentage of water received by customers that is not returned as sewage to the WWC pipe network;
- $I\&I\,[m3/year]$ is the annual inflow and infiltration volume to the WWC pipe network;
- $population(t)$ is the population number in year t.

$$BOD\,(t) = \frac{(BOD_0)\times population(t)}{\frac{365}{1000}\times WD(t)\times(1-CUF)\times popuation\,(t)+I\&I\,(t)} \tag{3.3}$$

where

- t $[year]$ is the current time;
- BOD $[kg/capita/year]$ is the mass of dissolved oxygen needed by aerobic biological organisms to break down organic material presented in wastewater sample in year t;
- $BOD_0[kg/capita/year]$ is the initial BOD;
- $\frac{365}{1000}$ $[(\frac{day}{year})/(\frac{m^3}{liter})$] is the conversion factor to convert days to year and liter to cubic meter;
- $WD(t)$ $[liter/capita/day]$ is the average daily water demand of a residential user in year t;
- CUF [%] is the percentage of water received by customers that is not returned as sewage to the WWC pipe network;
- $I\&I$ $[m3/year]$ is the annual inflow and infiltration volume to the WWC pipe network;
- $population(t)$ is the population number in year t.

3.3.3 Finance sector

In this section, the new models developed for the WWC and WWT finance sectors are described in detail.

3.3.3.1 WWC pipe network finance model

The operation and maintenance cost of pipes in different ICG-categories and the user-fee calculation are modeled similar to the Rehan (2011) model. The revenues are generated from the WWC_Fee $[\$/m^3]$ and $WWC\_Service\_Charges$ $[\$/month]$. The connection-service charges are based on the water-meter sizes and are collected on a monthly bases. The number of meters in each size is assumed to be increased by the same rate as the population growth rate. The service charges inflation is considered to be equal to the non-residential buildings construction-price-index (NRB CPI) which is reported as 3.7% per annum by Statistics Canada (2018).

The new parts of the model consist of separate fund-balance stocks for operational and capital expenses which are presented as $WWC\_Op\_FundBalance$ [\$] and $WWC\_Cap\_FundBalance$ [\$] respectively in Figure 3-8. In the new finance module, the generated revenues are primarily allocated to pay for the $WWC\_Maintenance\_Expenses[\$/year]$ and $WWC\_Debt\_Services[\$/year]$, and the remaining is transferred to the capital fund balance ($WWC\_Operation\_Over\_Fund$ [$\$/year$]) for paying the capital costs of WWC pipe network rehabilitation and expansion.

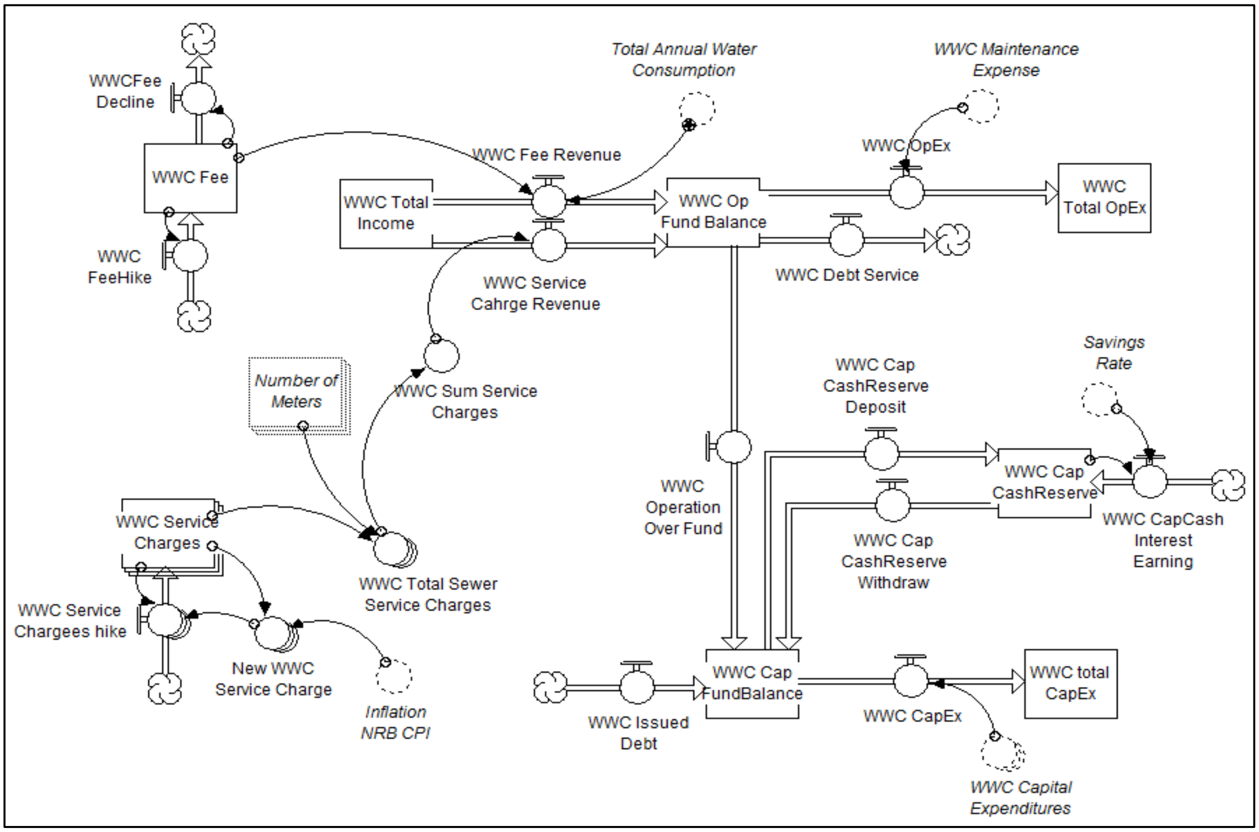


Figure 3-8: WWC finance model.

The WWC utility has the option to issue debt to maintain a zero capital fund balance if the revenue from operational fund balance is not sufficient to pay the capital expenses. In the opposite scenario, the surplus revenue can be reserved for future lump capital expenses. Separation of the two fund balance accounts in the present model restricts payment for operational expenses from issued debt or reserved cash.

3.3.3.2 Wastewater treatment-plant finance model

A novel model is developed for the WWTPs finance sector. Similar to the WWC finance structure, the surplus revenues are available to lower fund-balance stocks presented in Figure 3-9.

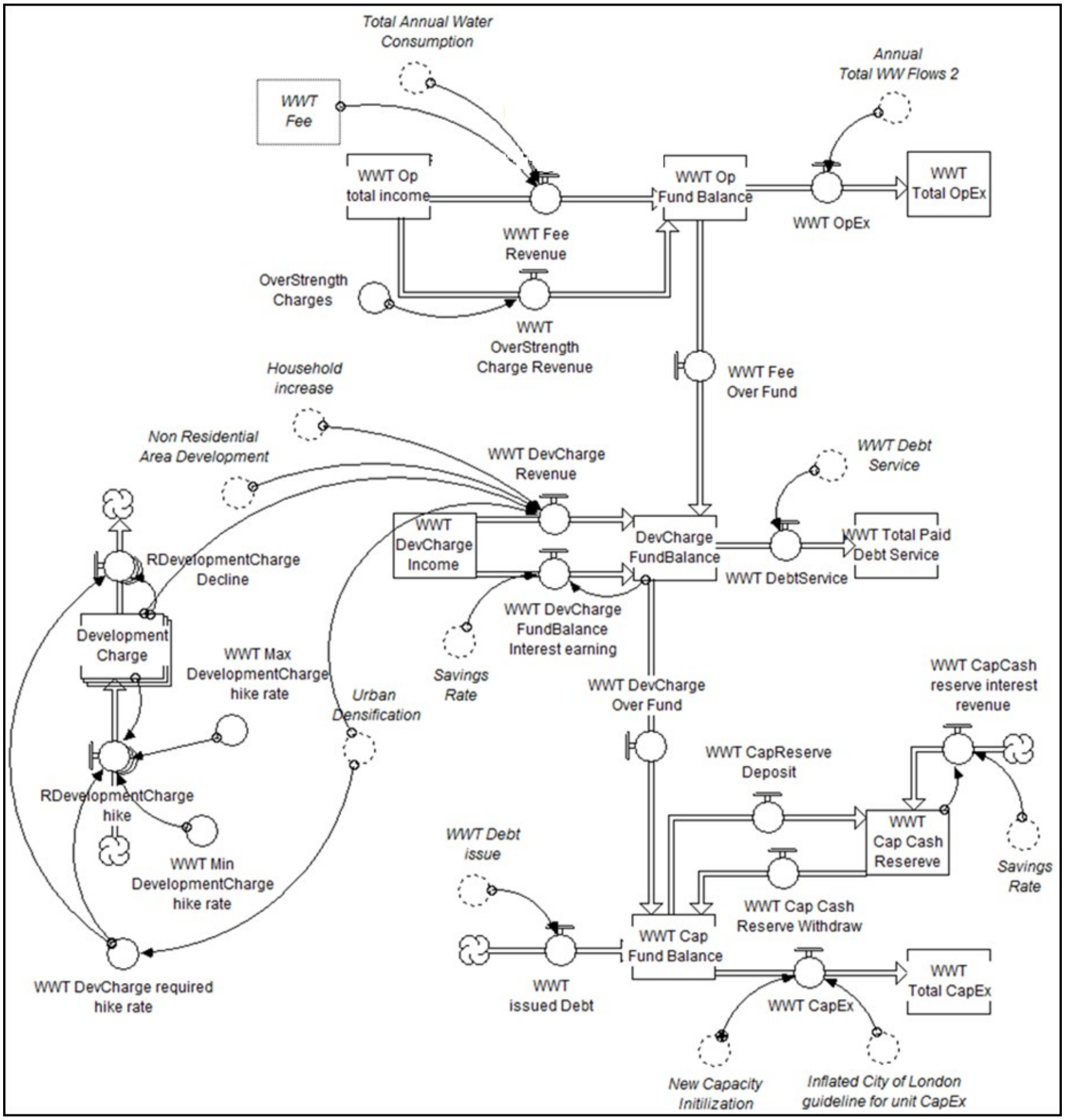


Figure 3-9: WWT finance model.

The revenues generated from collecting the user-fees ($WWT\_Fee[\$/m^3]$) and $OverStrength\_Charges$ [$\$/year$] and are primarily paid for the operational expenses (WWT_OpEx [$\$/year$]). $Development\_Charges$ [$\$/unit\ and\ \$/m^2$] are allocated to recover the cost of developing new urban area and are governed by the Province of Ontario under Development Charge Act (Government of Ontario 2018). If the utility has debt, the revenues from development charges are first allocated to pay debt services ($WWT\_DebtService$ [$\$/$

$year$]), and the surplus becomes available for paying the capital expenses (WWT_CapEx [\$/ $year$]).

The total development charge (DC) is the sum of the residential and non-residential development charges which are calculated using Equation (3.4) and (3.5) respectively

$$DC_{residential}(t) = N_{residential} \times [(1 - UDI) \times\ S\ (t) + (UDI \times A(t))] \tag{3.4}$$

where

- t [$year$] is the current time;
- $DC_{residential}$ (t) [\$/$year$] represents the revenue of issuing permits for residential building constructions in year t;
- $N_{residentail}$ [$household/year$] is the number of households added to the current population in year t;
- UDI [%] represents the urban densification index;
- $S\ (t)$[\$] is the development-charge for single and attached houses in year t;
- $A\ (t)$[\$] is the development-charge for apartments and lodging units in year t.

$$DC_{non\_residential}(t) = AD_{non\_residential} \times [(1 - UDI) \times\ NR\ (t)] \tag{3.5}$$

where

- t [$year$] is the current time;
- $DC_{non\_residential}$ (t) [\$/$year$] represents the revenue of issuing permits for construction of non-residential buildings in year t;
- $AD_{non\_residentail}$ [$m^2/year$] is the new area permitted for building commercial, institutional or industrial buildings in year t;
- UDI [%] represents the urban densification index;
- $NR\ (t)$[\$] is the development-charge for non-residential area development in year t;

When $UDI = 0\%$, the model will simulate the no urban densification scenario, non-residential area are developed at the same rate as the population growth rate, and only single houses and townhouses will be built to accommodate new population. In contrast, when the $UDI = 100\%$, the model assumes that only apartments and lodging units will be built. The most probable policy would be a 50% urban densification.

If the cash-reserve scenario is selected, the surplus cash will be reserved to up to 50% of the replacement value of WWTPs in reserve ($WWT\_CapCash\_Reserve[\$/year]$) for paying future capital expenses. If the revenues into capital fund balance ($WWT\_Cap\_FundBalance$ [\$]) are insufficient to pay for the capital-work expenses, the utility has the option to issue debt to maintain a zero fund balance.

3.3.3.2.1 Operational and capital expenses of WWTP systems

This section describes the calculation of capital and operational expenses at WWTPs. The U.S. EPA (1980) methodology or the utilities guidelines can be used for estimating the unit capital expenses of building new WWTP capacity. The unit operational expenses consists of four main elements: 1) employees or manpower costs, 2) utilities costs, 3) chemical and material costs, and 4) maintenance costs. Figure 3-10 shows the proportional expenses in each elements for a WWTP in the City of Toronto. A similar approach and results can be found in the study done by Tsagarakis, Mara, and Angelakis (2003).

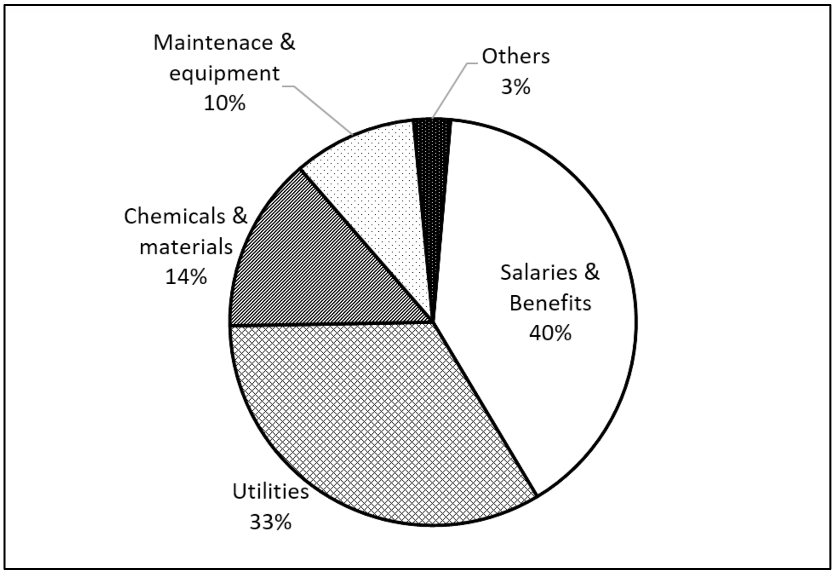


Figure 3-10: Average annual WWTP operational cost of Highland Creek WWTP from 2005 to 2015.

Several survey studies have been conducted to develop mathematical models for predicting the operational cost of WWTPs. Hernandez-Sancho, Molinos-Senante, and Sala-

Garrido (2011) have parametrized the OpEx and CapEx based on the wastewater flow rate, contaminant removal rate, and the age of WWTPs, by analyzing the data for 341 Spanish WWTPs. Their study demonstrates that operational expenses in WWTPs increase with an increasing rate of SS removal.

Balmér and Mattson (1994) have studied 20 homogenous WWTPs in Sweden to assess the manpower, electricity, chemical, and maintenance costs of the WWTPs against the increasing population equivalent ($P_{eq.}$), which is defined as an equivalent population of loading 60 grams per day per capita BOD in the wastewater system (European Commission-Environment 2007). Their analysis shows that the unit cost of electricity, manpower, and maintenance at WWTPs declines with an increasing $P_{eq.}$, while the unit cost of chemicals remains steady. Fraas and Munley (1984) have analyzed the financial reports of 178 WWTPs in the United State and proposed a function for estimating the marginal operational and capital expenses of a WWTP based on increasing wastewater volume and BOD concentration. Their model suggests exponential growth in the unit operational expenses with increasing inflow volume and BOD concentration.

Since the majority of WWTPs are not operating at their optimum condition, finding a universal predictive function is not possible. The functions that are suggested in the reviewed studies rely heavily on their own collected data and are not developed for the specific purpose of this study. Although these mathematical relationships can be applied, it will be more relevant and intuitive to use existing WWTP data and develop a first-order relationship. It is also reasonable to assume that the amount of polymer used for sludge thickening and dewatering (which contributes 60% of the total chemical costs) is a function of the SS concentration. Similarly, the amount of natural gas used for sludge incineration (which contributes 99% of the total utility costs) is directly related to the amount SS concentration. If zero SS is coming to the WWTPs, no or little sludge will be generated. Thus, no polymer would be needed for sludge dewatering, and no natural gas would be needed for sludge incineration.

Highland Creek WWTP data from years 2005 to 2015 are used to plot Figure 3-11 and Figure 3-12, which respectively present the first order regression analysis of the chemical and utility costs based on the SS concentration of wastewater inflow at WWTP respectively. Both regression lines pass through the origin.

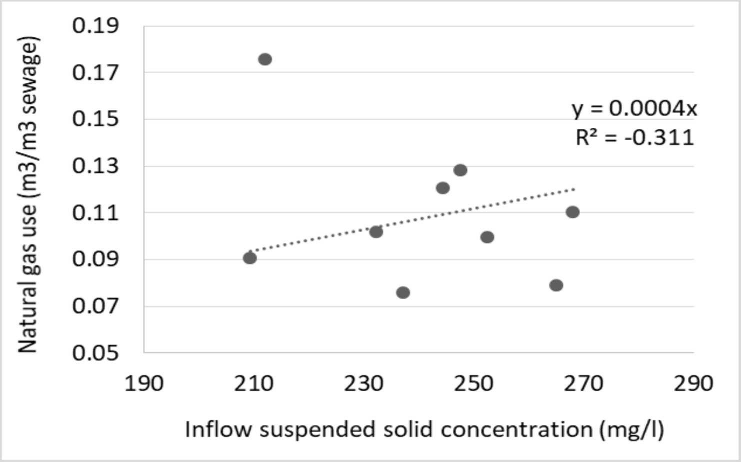


Figure 3-11: Unit cost of natural gas use based on SS concentration.

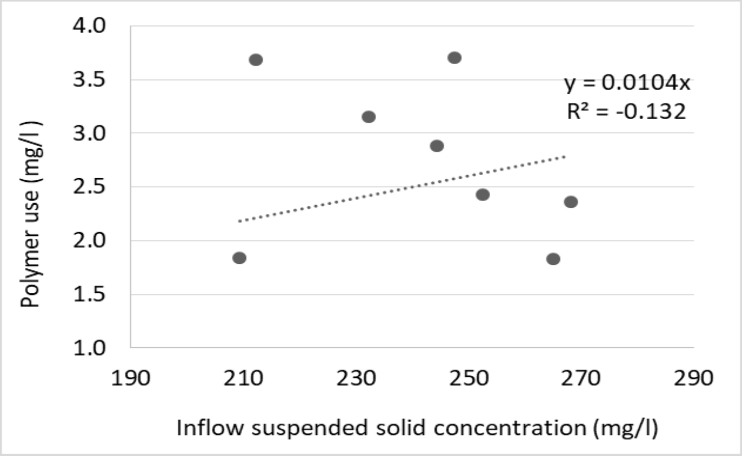


Figure 3-12 Unit cost of polymer use based on SS concentration.

Salaries and employment costs are functions of the treatment capacity or the volume of treated wastewater (Balmér and Mattson 1994). The maintenance cost for replacing or repairing machinery and equipment is considered to be an annual fixed cost.

3.3.4 Natural environment sector

The greenhouse gas (GHG) emission indicator is calculated as a proxy for the environmental sector. The following sections describe the calculation method.

3.3.4.1 GHG calculation

The GHG module presented in Figure 3-13 is developed to capture the variations and dynamics in GHG emissions as the results of different asset management scenarios.

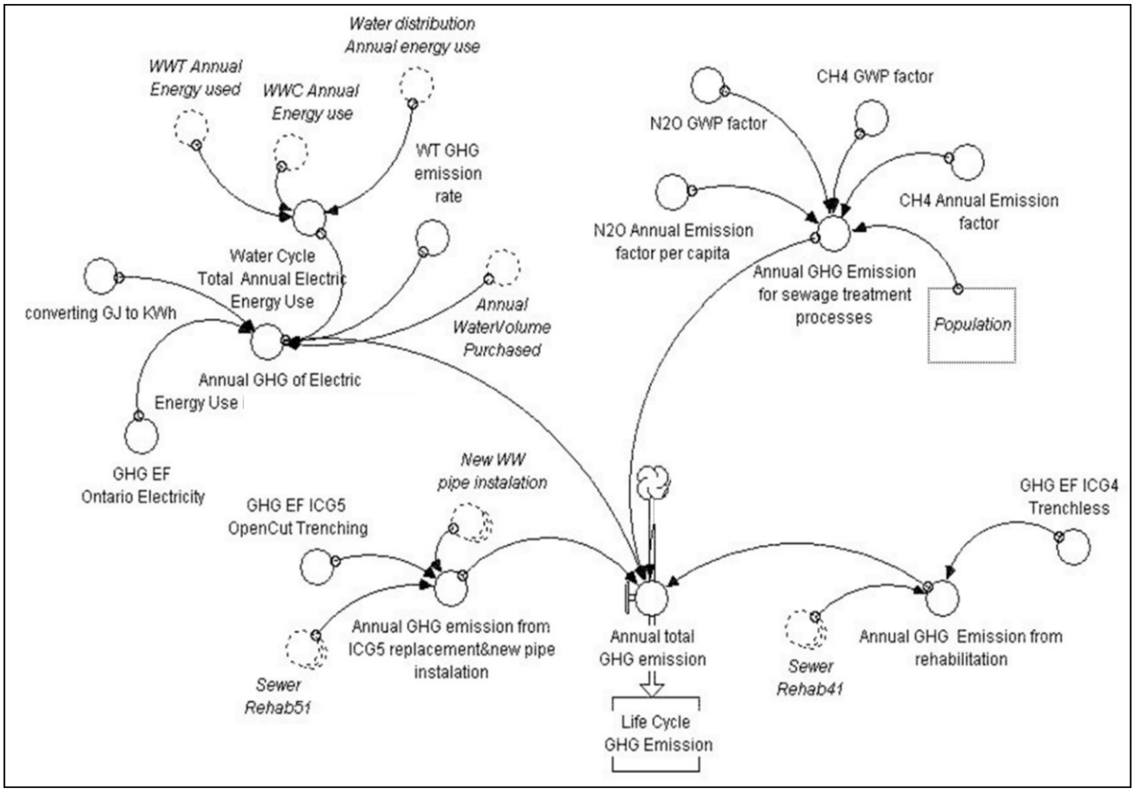


Figure 3-13: Life-cycle GHG emission calculation model.

The annual total GHG emission is comprised of the following variables, which are described in the next subsections

- Annual GHG emission from wastewater treatment processes;
- Annual GHG emission from electric energy-use;
- Annual GHG emission from ICG5 replacement and new pipe installations;
- Annual GHG emission from ICG4 rehabilitation pipes.

3.3.4.1.1 GHG emission of treatment processes

Three sources of GHG emissions are attributed to the treatment processes: CO_2, CH_4, and N_2O gas emissions. The CO_2 gas emission is classified as "biogenic" emission–since it would otherwise have been emitted trough natural process of decay –and is not accounted in most referred to protocols such as the Intergovernmental Panel on Climate Change (IPCC) or the Local Government Operations Protocols (LCOP).

The annual methane gas (CH_4) and nitrous oxide (N_2O) emissions are estimated based on the Intergovernmental Panel on Climate Change (IPCC 2006) protocol. Annual methane gas emission is calculated using Equation (3.5) as

$$CH_4(t) \ = \left[\sum\left(U_i \times T_{ij} \times EF_j\right)\right] \times (I\_BOD(t) - S\_ \ BOD(t)) - R \tag{3.5}$$

where:

- t $[year]$ is the current time;
- $CH_4(t)$ $[kg/year]$ represents the mass of methane gas emissions in year t;
- Ui [%] represent the fraction of population in income group i as rural, urban high income, and urban low income;
- T_{ij} [%] indicates the treatment pathway j as centralized well managed aerobic treatment, overloaded aerobic treatment, anaerobic digester, etc., served for each group of people in different income groups or(i);
- EF_j $[kg/year]$ is the emission factor in each treatment pathway;
- $I_{BOD}(t)$ $[mg/l]$ is the BOD concentration of wastewater inflow at WWTP in year t;
- $S\_BOD(t)$ $[mg/l]$ is the BOD in removed sludge from WWTP in year t;
- R $[kg\ CH_4/year]$ represents the recovered methane gas from WWTP in each studied year.

In IPCC (2006) manual, 95% of Canadians are classified as high income people, and the most common wastewater treatment method are centralized aerobic wastewater treatment and lagoons for both domestic and industrial wastewater. In Ontario, almost the entire population is connected to centralized treatment systems where secondary-mechanical treatment are applied to remove most of organic matters (Environment Canada 2011). Based on the IPCC (2006) manual, the methane gas emission factor for well managed aerobic treatment systems is considered to be zero. The methane gas emission can be negative if the biogas from anaerobic treatment of wastewater sludge is used for heat and energy recovery.

The annual N_2O emission is calculated using Equation (3.6) as

$$N_2O(t) = P(t) \times 0.004 \tag{3.6}$$

where

- t $[year]$ is the current time;
- $N_2O(t)$ $[kg/year]$ represents the mass of nitrous oxide emissions in year t;
- P(t) [capita] is the population in year t;
- 0.004 [kg/capita/year] is the mass of nitrous oxide emission per person per year (industrial and commercial discharges are also attributed to the residential users).

Therefore, the total annual GHG emissions from the wastewater treatment processes is calculated by Equation (3.7) as

$$GHG\ (t) = 23 \times CH_4(t) + 296 \times N_2O \tag{3.7}$$

where

- t $[year]$ is the current time;
- $GHG\ (t)$ $[kg/year]$ represents the equivalent mass of CO_2 gas emitted from wastewater treatment processes in year t;
- 23 $[kg\ CO_2/kg\ CH_4]$ represents the relative global warming potential of CH_4 gas compared to an equivalent mass of CO_2 gas;
- $CH_4(t)$ $[kg/year\ ]$ is the annual CH_4 emission calculated in Equation (3.5);
- 296 $[kg\ CO_2/kg\ N_2O]$ represents the relative global warming potential of N_2O gas compared to an equivalent mass of CO_2 gas;
- N_2O $[kg/year]$ is the annual N_2O emission calculated in Equation (3.6).

3.3.4.1.2 GHG emission of used energy

From a life-cycle perspective, energy-use accounting should be done for all life-cycle stages of a studied product or service, including the manufacturing of materials, construction of structures, operation and maintenance of wastewater-collection and rehabilitation and renewal of infrastructure parts, as well as the disposal of waste materials and end-of-life components.

Based on a study done by the United State Environmental Protection Agency (Cashman et al. 2014), more than 95% of energy-use is attributed to the operational and maintenance stages of water and wastewater systems. Therefore, the energy footprint modeling is centered on the operation, maintenance, and rehabilitation activities. Presented in Figure 3-14, the energy footprints of wastewater collection asset management activities are the sum of all activities listed below

- $Annual\_Energy\_use\_for\_sewage\_capital\_works$ $[gigajoule/year]$ which includes the energy used for new pipes installation and ICG4 pipes rehabilitation activities;
- $Annual\_Energy\_used\_for\_sewage\_collection$ $[gigajoule/year]$;
- $Annual\_Energy\_used\_for\_WWT[gigajoule/year]$;
- $Annual\_energy\_used\_for\_WT$ $[gigajoule/year]$;
- $Annual\_energy\_used\_for\_water\_distribution$ $[gigajoule/year]$;
- $Annual\_Energy\_use\_for\_sludge\_transportaiton$ $[gigajoule/year]$ to a central treatment facility such as incineration plant or landfill site;
- $Sludge\_treatment\_Energy$ $[gigajoule/year]$ produced or used in sludge treatment processes.

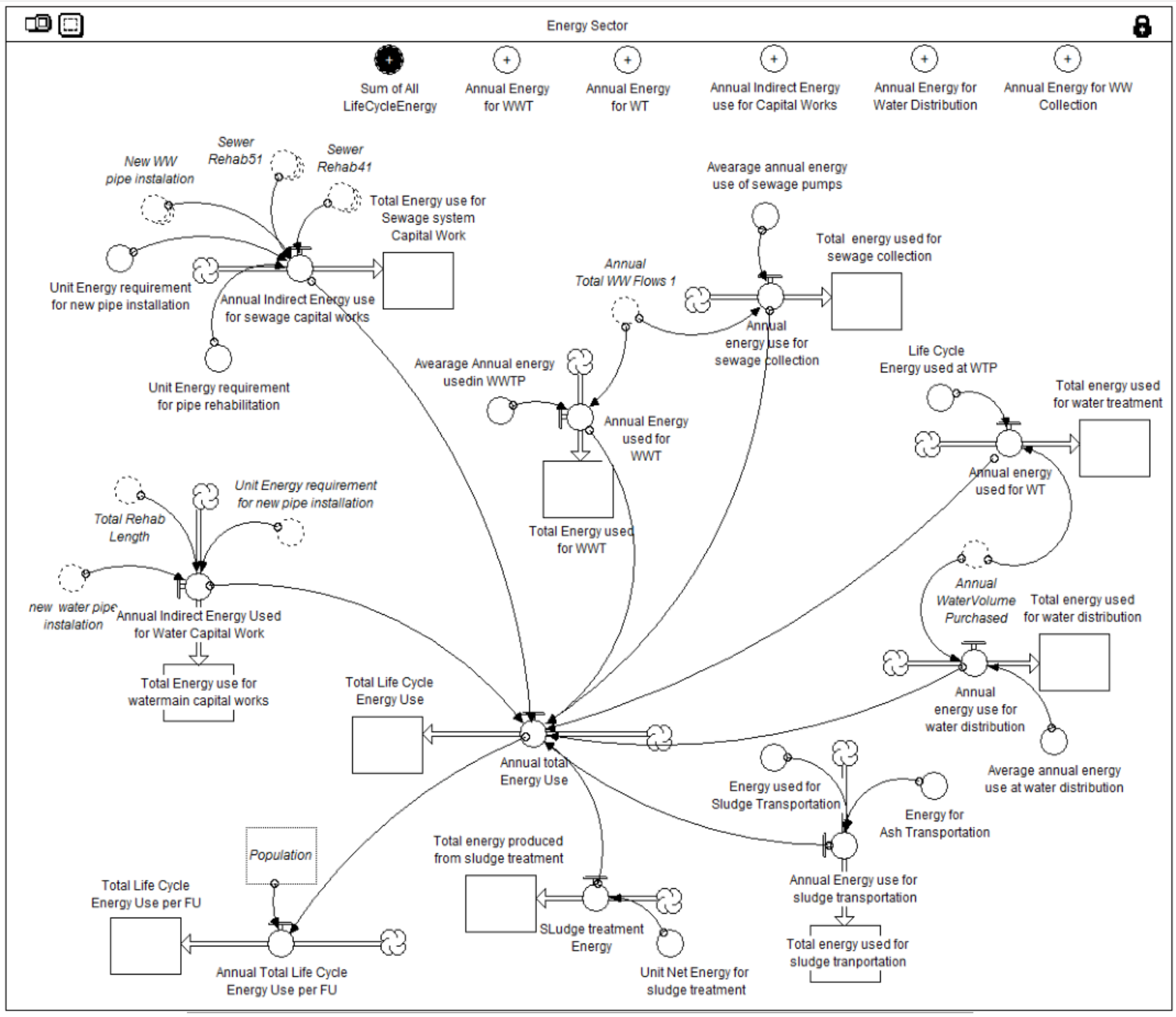


Figure 3-14: Energy sector model.

The GHG emission factors are used to convert the energy-use rate to kg CO_2 eq. for various energy resources. The GHG emission factor for one kwh electrical energy is calculated based on the energy resources used to generated 1 kwh electricity, which is considered to be 125 g/kwh in Ontario (Sahely et al. 2006).

3.3.4.1.3 GHG emission from urban road system

Rehabilitation activities, particularly when done by open-cut trenching technologies, can lead to traffic delays and consequently more GHG emissions from cars' engine-fuel combustion

(Rehan and Knight 2007). Average GHG emission factors for traffic delays are calculated using the methodology described in Rehan and Knight (2007). The annual GHG emissions form traffic disturbances can be calculated using Equation (3.8) as

$$GHG\ road\ system\ (t)\ =\ 2 * ICG4\ (t)\ +\ 64 * (ICG5 + NSP)$$

where

- t $[year]$ is the current time;
- $GHG\_raod\_ststem\ (t)$ $[kg/year]$ represents the equivalent mass of CO_2 emitted from traffic disturbances in year t;
- 2 $[kg\ CO_{2eq.}/m]$ represents the GHG emission factor for rehabilitation of ICG4 pipes in year t by using trenchless technologies;
- $ICG4(t)[m/year]$ is the length of ICG4 pipes rehabilitated in year t;
- 64 $[kg\ CO_2/m]$ represents the GHG emission factor for replacement of ICG5 or installation of new WWC pipes using open-cut technology in year t (daily traffic is assumed to be 3,500 vehicles/day);
- $ICG5[m/year]$ is the length of ICG5 pipes being replaced in year t;
- $NSP[m/year]$ is the length of new WWC pipes being installed in year t.

3.4 Model use

To facilitate the use of the SD model, a user control panel is designed at the user-interface layer of the Stella software. It includes a set of data-entry tables and keys for adjusting several policy levers used for developing scenarios. In this section, each component of the control panel design is described in detail.

3.4.1 Initial data entries

Several data-entry tables that specify the initial data required in each sector before asset management scenarios are run provided at the user-interface layer of the SD model. Initial data related to the physical infrastructure, finance, natural environment, and consumer sectors are presented in Table 3-1, Table 3-2, Table 3-3, and Table 3-4 respectively.

Table 3-1: Data entry for physical infrastructure sector.

Data entry	*Unit*	*Practical range*
Initial length of pipes based on material and internal condition grade	km	$0 \sim 10^3$
Initial number of water meters based on pipe diameter	-	$0 \sim 10^5$
Initial capacity of WWTPs	m^3/day	$0 \sim 10^{10}$
Initial total infiltration and inflow	m^3/year	$0 \sim 10^{10}$
Initial equivalent suspended solid generation	kg/year/capita	$40 \sim 70$
Initial equivalent BOD generation	kg/year/capita	$50 \sim 70$

Table 3-2: Data entry for finance sector.

Data entry	*Unit*	*Practical range*
Price elasticity of water demand for residential users	-	$0 \sim 1$
Average household income	$/year	$50000 \sim 90000$
Initial WWC cost	$/m^3	$0.1 \sim 10$
Initial wastewater treatment cost	$/m^3	$0.1 \sim 10$
Initial debt/reserve of utility (for WWC model)	$	$0 \sim 10^9$
Initial debt/reserve of region (for WWTP model)	$	$0 \sim 10^9$
Annual revenues from industries for over strength wastewater discharge	$/year	$0 \sim 10^6$
Unit maintenance cost of WWC pipes in each ICG class	$/m/year	$2 \sim 10$
Unit development charge for apartments/lodges	$/unit	$1000 \sim 3000$
Unit development charge for houses/townhouses	$/unit	$2000 \sim 5 \times 10^4$
Unit development charges for non-residential areas	$/m^2	$0.1 \sim 10$
Initial service charges based on water meter sizes	$/m	$200 \sim 2000$
Unit cost of CIG4 pipes' rehabilitation	$/m	$400 \sim 600$
Unit cost of ICG5 pipes replacement	$/m	$700 \sim 1000$
Inflation rate for electrical energy cost	-	$0 \sim 5$
Inflation rate for non-residential building construction cost	-	$0 \sim 7$
Fixed borrowing rate	-	$0 \sim 7$
Fixed saving rate	-	$0 \sim 5$

Table 3-3: Data entry for natural environment sector.

Data entry	***Unit***	***Practical range***
Life-cycle energy used for pipes manufacturing	mega joules/kg	50 ~ 100
Life-cycle energy used for new pipe installation	mega joules/m	1000 ~ 2000
Life-cycle energy use for drinking water treatment	mega joules/m^3	0 ~ 3
Energy use for water distribution	mega joules/m^3	0 ~ 3
Energy use for wastewater collection	mega joules/m^3	0 ~ 1
Life-cycle energy used for wastewater treatment	mega joules/m^3	0 ~ 3
Life-cycle energy used for treatment plant construction	mega joules/m^3	0 ~ 1

Table 3-4: Data entry for consumer sector.

Data entry	***Unit***	***Practical range***
Initial population	capita	$0 \sim 5 \times 10^{9}$
Average household size	capita	2 ~ 4
Population growth rate	percent/year	0 ~ 100
Initial water demand for residential users	liter/day/capita	150 ~ 300
Minimum water demand for residential users	liter/day/capita	100 ~150
Initial water demand for Non-residential users	liter/year	$0 \sim 5 \times 10^{18}$
Bill hardship threshold	% of household income	0.1 ~ 100
Initial number of residential apartment & lodging	-	$10 \sim 5 \times 10^{5}$
Initial number of houses & townhouses	-	$10 \sim 5 \times 10^{5}$
Initial non-residential area	m^2	$10 \sim 5 \times 10^{7}$
Initial WWC fee for residential user	$/ m^3	0.01 ~ 10
Initial WWC fee for non-residential user	$/ m^3	0.01 ~ 10
Initial WWC free residential user	$/ m^3	0.01 ~ 10
Initial wastewater treatment free non-residential user	$/ m^3	0.01 ~ 10

3.4.2 Policy levers settings

The policy setting keys are provided at the user-interface layer of the model to facilitate applying the SD model and defining various scenarios. Figure 3-15 presents a snapshot of the policy levers provided in the user-interface layer.

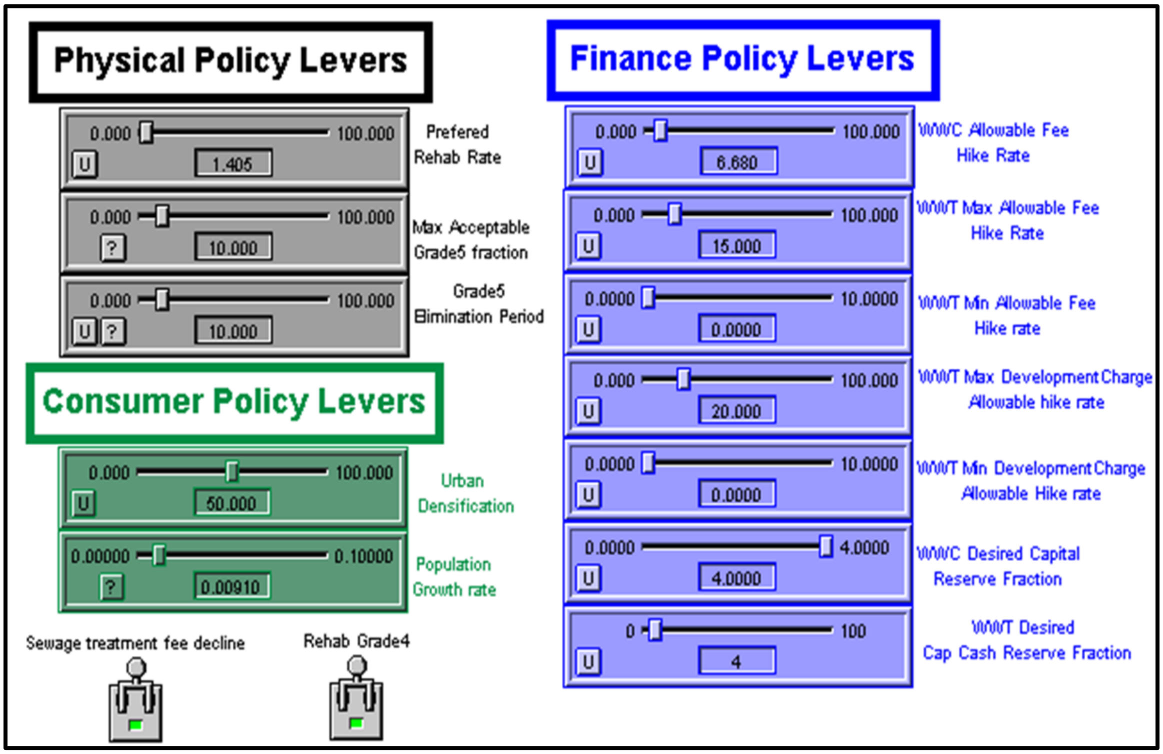


Figure 3-15: A snap shot of the policy levers at the interface layer.

Rehan et al. (2011a) and Ganjidoost et al. (2018) used three policy levers adopted from the physical sector to test various asset management strategies for WWC systems. The $Max\_Acceptable\ Grade5\_fraction$ [%] policy lever is used to define the percentage of network that can acceptably be in the worst condition grade (ICG5). This value reflects the maximum tolerance of service users and the operational capacity of the studied utility to deal with ICG5 pipes failures, and can be adjusted to any value from 0 to 100%.

The maximum rate of WWC pipe rehabilitation is defined by using the $Preferred\_Rehab\_Rate$ [%] policy lever. A least value for this policy lever is determined by trial and error method. It should be noted that the actual rate of rehabilitation in each year is constrained by the capital fund balance, as well as by the length of ICG5 pipes, regardless of the defined rehabilitation strategy.

If the ICG5 fraction exceeds the $Max\_Acceptable\_Grade5\_fraction$ [%], the model will adjust to a new rehabilitation rate above the preferred rehabilitation rate to reduce the ICG5 percentage to the acceptable level within the limited number of years specified by the

$Grade5\_Elimination\_Period$ $[year]$ policy lever. In that period, the WWC utility should generate enough revenue to support sufficient capital expenses for reducing the ICG5 percentage to below the acceptable level.

The $Rehab\_Grade4$ $[-]$ switch provides the option to include rehabilitation of ICG4 pipes in the asset management plan. If the Rehab_Grade4 switch is on, the capital fund remaining after spending on ICG5 replacement and WWC pipe installation for network expansion will be allocated for rehabilitation of the ICG4 pipes.

Seven finance policy levers have been developed for the WWC and WWT finance sectors. The $WWC - Allowable\_Fee\_Hike\_Rate$ [%] and $WWT\_Max\_Allowable\_Fee\_Hike\_Rate$ [%] are used to constrain the annual WWC and WWT fee increases respectively. As discussed in Section 3.2, the WWC and WWT fees are increased/decreased in respond to the additional/reduction of operational expenses for the WWC and WWT systems and form the (R1) and (R2) reinforcing loops, respectively.

When the $Sewage\_treatment\_fee\_decline$ $[-]$ switch is turned on, the WWT fee will rise or fall according to the changes in annual operational expenses. When the switch is turned off, the WWT fee hike will be constrained by the minimum fee hike rate specified by the $WWT\_Min\_Allowable\_Fee\_Hike\_Rate$ [%] policy lever. This allows the WWT-fee based revenue to exceed the current operational expenses and transfer surplus cash to the development charge fund-balance to spend on capital expense. The develop-charge hike rates are always constrained by a minimum hike rate specified by the $WWT\_Min\_Allowable\_DevelopmentCharge\_Hike\_Rate$ [%] policy lever. The minimum hike rates can receive any value between 0 and the maximum hike rates.

The $WWC\_Desired\_Capital\_Reserve\_Fraction$ [%] and $WWT\_Desired\_Cap\_Cash\_Reserve\_Fraction$ [%] policy levers are set similar to the Rehan et al. (2011) and Ganjidoost et al. (2018) models. The maximum reserve capacity for the WWC and WWTP finance sectors are defined based on 4% replacement value of the WWC and 100% replacement value of the WWTP asset respectively.

It is important to note that the minimum-fee hike rate policy lever leads to reserve cash in opposite circumstances than the cash reserving policy lever. By applying the cash reserving policy lever, the model will adjust the WWT fee up to the maximum fee-hike rate, thus starting cash reserving as soon as possible to fill-up the defined reserve capacity. However, by applying the minimum-fee hike rate policy lever, the model will adjust the WWT fee to the minimum fee-hike rate, thus starting cash reserving only during the years when the WWT fees require no increase to pay operational expenses.

The $Population\_Growth\_rate$ [%] and $Urban\_Densification$ [%] index are the two policy levers employed to formulate future scenarios related to the consumer sector, both of which can receive any value from 0 to 100 percent. A 0% urban densification scenario will cause the WWC pipe network length to grow at the same rate as the population growth rate, which incurs capital and operational expenses for the WWC system. In contrast, in a 100% urban densification scenario, new population is served within the current WWC pipe network, which avoids the installation and operation of new pipes.

3.4.3 Graphical presentation of output results

The impact of strategic decisions on the asset management of wastewater infrastructure systems can be monitored at the user-interface layer as well (Figure 3-16). Some of the key output-variables that are plotted in separate or combined diagrams to represent the WWC and WWTP system dynamic behaviors over the simulation period are presented in Table 3-5.

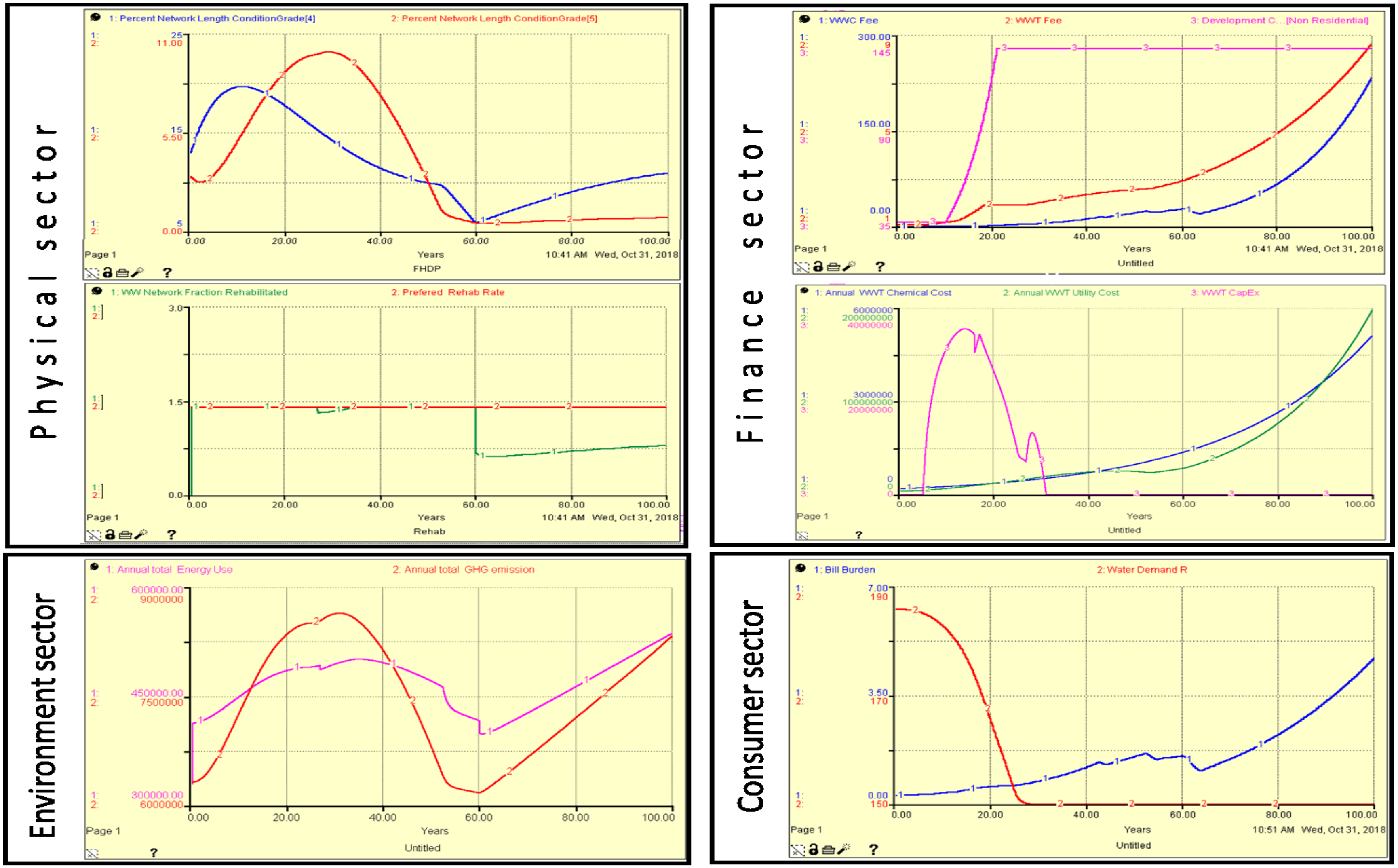


Figure 3-16: Presentation of diagrams at the user-interface layer.

Table 3-5: list of out-put variables plotted in the user-interface layer of the SD model.

Variable	***Unit***	***Description***
Physical sector		
$Actual\_Rehab\_Rate\ (t)$	[%]	Fraction of WWC pipe network that is been replaced or rehabilitated in year t
$ICG5\_Fraction\ (t)$	[%]	Fraction of ICG5 pipes length that is in service within the WWC pipe network in year t
$ICG4\_Fraction\ (t)$	[%]	Fraction of ICG4 pipes length in WWC pipe network in year t
$Avg\_ICG\_Network(t)$	$[ICG]$	Average internal condition grade of the network in year t
$Network\_Expns(t)$	$[m]$	Length of WWC pipe network expanded in year t
$Generated\_WW\_Res(t)$	$[m^3/day]$	Sewage generated by residential users in year t
$Generated\_WW\_Non - Res(t)$	$[m^3/day]$	Wastewater generated by non-residential users in year t
$I\&I(t)$	$[m^3/day]$	Inflow and infiltration volume in year t
Finance sector		
$WWC\_Fee\ (t)$	[\$]	WWC fee hike rate for residential users in year t
$WWT\_Fee\ (t)$	[\$]	WWT fee hike rate for residential users in year t
$DevCharge\_Res\_Apt(t)$	[\$]	Development charges for building new residential apartments in year t
$DevCharge\_Res\_House(t)$	[\$]	Development charges for building new residential houses in year t
$DevCharge\_NonRes(t)$	[\$]	Development charges for development of non-residential areas in year t

Variable	***Unit***	***Description***
$WWC\_Op\_FB(t)$	[\$]	Operational fund balance of WWC system in year t
$WWC\_Cap\_FB(t)$	[\$]	Capital fund balance of WWC system in year t
$WWT\_Op\_FB(t)$	[\$]	Operational fund balance of WWT system in year t
$WWT\_CevCharge\_FB(t)$	[\$]	Development charge fund balance of WWT system in year t
$WWT\_Cap\_FB(t)$	[\$]	Capital fund balance of WWT system in year t
$WWC\_Debt(t)$	[\$]	Amount of issued debt for capital work expenses for WWC pipe network system in year t
$WWT\_Debt(t)$	[\$]	Amount of issued debt for capital work expenses for WWTP capacity upgrading in year t
$OpEx\_WWC(t)$	[\$]	Operational and maintenance expenses of WWC system in year t
$CapEx\_WWC(t)$	[\$]	Capital expenses of WWC system in year t
$OpEx\_WWT(t)$	[\$]	Operational and maintenance expenses of WWT system in year t
$CapEx\_WWT(t)$	[\$]	Capital expenses of WWT system in year t
$Reserve\_WWT\_Cap$	[%]	Fraction of extra capacity in WWTP system in year t
Natural environment sector		
$Energy\_Footprint$	$[gigajoules]$	Total energy used in WWC and WWTP systems in year t
$Total\_GHG$	$[tone\ CO_2]$	Total direct and indirect greenhouse gas emissions in year t

Variable	***Unit***	***Description***
Consumer sector		
$Water\_demand\_Res$	$[l/c/d]$	Average daily water demand of residential users in year t
$Bill\_Burden$	[%]	Fraction of an average household income which should be paid for WWC and WWT services

3.5 Validation and verification

Various testing methods has been suggested by Sterman (2000) to validate and establish confidence for a developed SD model. This section describes the suggested testing methods and procedures taken to validate the present SD model for WWT and WWC systems.

1. Dimensional consistency: this test checks the consistency of dimensions in each equations used at the detailed component level of an SD model. Forrester (1969) emphasizes that the validity of an SD model rests on the validity of its details, as "an endless variety of invalid components can exhibit the same apparent system behavior". This test was implemented on the present SD model by conducting the built-in unit-consistency checking function in the Stella software. The dimensions of all variables within the equations in the present models are provided in Appendix A.
2. Parameter assessment: the purpose of this test is to ensure that the variables used in an SD model are consistent with the descriptive and numerical knowledge of the system. The present SD model is built on available knowledge and information presented in peer-reviewed scientific journal articles. When the numerical data were available, statistical analysis have been conducted to estimate the parameters needed in the model, e.g., the unit cost of wastewater treatment is parametrized in Section 3.3.3.2.1 by analyzing the Highland Creek WWTP data from years 2005 to 2015.

3. Integration error: the purpose of this test is to check the sensitivity of the results to the choice of time-steps. In this model, the consistency of the results was compared for repeated simulations with shortened time-steps, as presented in Equation (3.9)

$$\Delta t = {}^{1}\!/_{2^n} \tag{3.9}$$

where

- Δt $[time]$ is the fraction of initial t;
- t $[year]$ is the initial simulation time-unit;
- n = 1, 2, 3,...

4. Extreme condition or reality checks: the aim of this test is to check the behavior of the system in extreme conditions, and it is implemented for likely and unlikely scenarios to check the representations of real world and extreme conditions respectively, e.g., in Section 2.5.2.4, the maximum (100%) and minimum (0%) urban densification indexes are selected to simulate extreme future urban development scenarios and to compare the results with the future probable scenario of 50% urban densification.

5. Boundary adequacy: this test assesses the appropriateness of the modeled system boundary. The present WWT model has extended the system boundary of the WWC model developed by Rehan et al. (2011) to change the WWT fee in the finance sector from an exogenous variable to an indigenous one. Other plausible extensions have been presented to experts and reviewed in relevant literature to assess their significance in changing the system behavior and final results.

6. Structure assessment: the purpose of this test is to check the consistency of the model structure with descriptive knowledge of the system. The structural defects are usually exposed when the model fails to exhibit rational behavior for an individual decision rule (Sterman 2000**).** The consistency of the model results with expected outcomes are checked at various aggregation levels; e.g., in Section 2.5.3,

the WWC pipe network length remained constant as expected when the population growth was set to zero.

While Coyle (1977) emphasized dimensional consistency, he believed that “the best test of confidence in a model is the knowledge that it has been carefully built up in conjunction with the management [...] to do the same thing as the real system and for the same reason”. In this regard, the developed SD model has been constructed in close corroboration with asset managers at partnered municipalities, who provided their insights and feedback at different stages of model development.

Coyle and Exelby (1999) argue that there are no absolutely objective validation tests as there are always inherent necessary assumptions being applied relevant to the purpose of a particular SD model. They suggest that an objective validation is achieved when the SD model is widely accepted by the community of practitioners. With this point in mind, the should be noted that academic and industrial societies have praised and given awards to presentation of the developed SD model and case study findings.

3.6 Conclusions

This study makes four unique contributions.

1. It extends the system boundary of developed SD models for municipal wastewater infrastructure systems, presented in Rehan et al. (2011) and Ganjidoost (2016), to include the socio-economic feedback from wastewater treatment plant systems.
2. It advances the scope of the SD models presented by Rehan et al. (2011) and Ganjidoost (2016), to include the environmental consequences of strategic decisions related to asset management planning of wastewater infrastructure system.
3. Also, new policy levers, such as population growth and urban densification in the social sector, and minimum fee-hike rates in the finance sector, are employed to enhance the representation of real-world conditions in the asset management planning process.

4. The newly developed causal loop diagram allows decision makers to better understanding the interrelated behavior of social, environmental, and economic systems, so they can see the whole picture and communicate the issues more effectively to other stakeholders.

The present SD model has been developed as part of the sustainability assessment framework introduced in the previous chapter. The next chapter demonstrates the application of the SD model in the sustainability assessment of strategic decisions related to wastewater collection asset management. It shows that considering the interrelation and feedback mechanism between the WWC pipe network and WWTP systems will allow users to find synergistic savings and opportunities when planning for the sustainability of these assets.

Chapter 4

Sustainability assessment of strategic asset management planning decisions for wastewater infrastructure systems

Abstract

The aim of this study is to implement the framework proposed in Chapter 2 to the working system dynamics model developed for municipal wastewater collection and treatment systems presented in Chapter 3. The utility and advantage of the proposed framework is demonstrated by evaluating the life cycle sustainability impacts of two alternative asset management strategies presented for the wastewater collection (WWC) system of a city in Southern Ontario.

It is shown that the application of the sustainability assessment framework, which applies system dynamics (SD) and life-cycle assessment (LCA) tools, can help to project the sustainability outlook of various strategic decisions for the asset management of water and wastewater infrastructure systems. The sustainably assessment results can inform decision makers about the long-term consequences of their strategic decisions on water and wastewater infrastructure assets and enable them to find synergistic cost savings and opportunities when planning for the sustainability of these assets.

4.1 Introduction

The government of Canada has announced the $53-billion “New Building Plan” for rejuvenation of Canadian public infrastructure, the largest infrastructure investment in the nation’s history (Infrastructure Canada 2018). The rehabilitation and expansion of municipal infrastructure, including water and wastewater systems, will not happen without consequences to social, environmental and economic systems. Thus, water and wastewater utilities should consider the long-term sustainability impacts of their decisions when developing their policies and strategic asset management plans.

The development of socially acceptable, environmentally friendly, and financially viable asset management plans compels understanding of the behavior of social, environmental, and economic systems. The complexity of planning decisions is compounded when different economic, social, and environmental dimensions of the challenge are inherently interrelated. Moreover, it is realized that a strategic asset management plan should include assessment of impacts to/from other affected systems upstream and downstream. Based on recent Asset Management Planning for Municipal Infrastructure regulation (Ontario Regulation 588, 2017), municipalities are obligated to coordinate the asset management plans of infrastructures that are connected or interrelated with those of upper-tier municipalities, neighboring municipalities, or jointly owned municipal bodies when preparing strategic asset management policies for their core assets.

The impacts from upstream water distribution systems is discussed by Ganjidoost (2016). Deterioration of water mains can cause them to break, and consequent increasing water leakage can increase infiltration and deterioration of the wastewater collection (WWC) pipe network system. WWC and wastewater treatment plant (WWTP) systems are also directly linked to each other. Wastewater from urban areas is collected in WWC pipe networks and sent to treatment facilities. The inter-relation and feedback mechanisms between the WWC pipe network system and downstream WWTP system was presented and modeled in Chapter 3 by using the system dynamic (SD) tool. It was shown that the changing wastewater volume and composition related to WWC pipe network systems have a direct impact on WWTPs' financial and operational management.

Chapter 2 introduced a novel sustainability assessment framework that applies system dynamics (SD) and life-cycle assessment (LCA) tools to project and evaluate the future sustainability performance of water and wastewater infrastructure systems. The goal of this chapter is to demonstrate the application of the proposed framework and its utility in developing policies and asset management strategies for integrated wastewater collection and treatment systems. To achieve this goal, implementation of the developed SD model for the wastewater infrastructure system of a medium-size municipality in Southern Ontario is presented for case-study demonstration. This case study represent atypical cities in Canada that own and operate both WWC and WWT infrastructure assets. In most Canadian municipalities, wastewater collection (WWC) and wastewater treatment plants (WWTPs) are owned and managed by separate municipal governments.

A central issue explored in the present study is the sustainability of the policy to accelerate the rehabilitation and replacement of deteriorated WWC pipes. The merits of this policy lever are evaluated by comparing the social, environmental, and financial costs of this strategic decision with those under current base-line strategy. Specifically, the focus of the sustainability assessment is to determine

- The annual cost to a residential user $[\$/year]$;
- The annual cost to the municipality $[\$/year]$;
- The annual greenhouse gas emissions$[Tone\ CO_2/year]$.

The following sections are arranged parallel to the steps defined in the sustainability assessment framework. Section 4.2 provides the background information and assumptions for the sustainability assessment framework application and demonstration case study. Alternative asset management scenarios are developed and discussed in Section 4.3. The results of the sustainability assessment framework application are presented and discussed in Section 4.4, and conclusions are drawn in Section 4.5.

4.2 Sustainability assessment framework application

4.2.1 Goal and scope definition

The goal of this case study is to assess the sustainability of strategic decisions for managing the WWC pipe network system for a medium-size municipality in Southern Ontario. The main attribute of the strategic asset management decision is the ‘acceptable maximum fraction of WWC pipes in worst internal-condition grade’ or ICG5─based on the UK-Water Research Center (WRc) condition-grade rating system. This policy lever was introduced in Rehan et al. (2011) to control the level of service or performance of the WWC system.

The subordinated policy levers, such as maximum rehabilitation and user-fee hike rates, should be adjusted to continue provision of wastewater collection as well as treatment services within the financial self-sustainability paradigm. The finance strategic decision is simplified to the pay-as-you-go strategy only. Borrowing or capital reserving options are not included in this assessment. The urban densification scenarios is restricted to a 50% urban densification rate.

The three indicators listed below are selected respectively from the financial, social, and environmental sectors for sustainability assessment:

1. The average affordability of the WWC and wastewater treatment services for a residential user who is expected to use the services for 100 years;
2. Life cycle cost of asset management to continue provisioning of the WWC and wastewater treatment services for the municipality;
3. Life-cycle greenhouse gas (GHG) emissions from WWC pipe network system and other infrastructure affected by the strategic decisions.

These sustainability assessment indicators are calculated for 100 years connection to the wastewater collection and treatment services, and represent the functional unit (FU) of the sustainability assessment. The 100-year timeframe is selected to capture the lifecycle of the pipes, and represents the greatest possible longevity within the infrastructure system (Rehan, et al. 2014). The system boundary for the environmental sustainability assessment is extended beyond the WWC pipe network system to assess the changes in GHG emissions from water treatment (WTP) and water distribution (WD) systems, WWTPs, and consequential GHG emission from road-traffic disturbances due to WWC pipe construction activities.

4.2.2 System dynamic modeling

The casual loop diagram (CLD), which presents the cause-and-effect interactions between the various components in the physical, social, finance, and natural-environment sectors, as well as the quantitative modeling and parameterization of the CLD, is discussed in Chapter 3. In the following section, initial data entries and assumptions needed for simulation of the proposed asset management strategies are described in detail.

4.2.2.1 Data inventorying

4.2.2.1.1 Physical sector

The physical sector consists of a combined WWC pipe deterioration model and a WWTP capacity-expansion model. The WWC pipe inventory is classified into five internal condition grades (ICG) using the UK Water Research Center rating system (WRc 2011), and into five different pipe materials. ICG1 represent the pipes in the best condition, and ICG5 represents the pipes in the worst condition. The remaining service life of each pipe and its maintenance cost are determined based on its condition grade and material, as described in Rehan et al., (2014) and Rehan et al., (2011). The distribution of pipes in each condition grade is presented in Table 4-1. This table shows a total 2795 km WWC pipe network, comprised of 1916 kilometers (km) of concrete pipes that are mostly in the ICG2 and ICG3 categories; 430 km of asbestos cement (AC) pipes and 243 km of pipes made of bricks and Vitrified Clay (VC) that are mainly in the ICG4 category; 185 km of Polyvinyl Chloride (PVC) and High Density Polyethylene (HDPE) in the best condition grade; and a remaining 21 km of metallic pipes such as Cast Iron (CI), Ductile Iron (DI) and Steel (St) pipes.

Table 4-1: WWC pipe inventory.

Pipe Material	***Length of pipes in each grade (km ICG)***				
	1	***2***	***3***	***4***	***5***
AC	0.8	342.7	77.9	8.0	0.3
brick + VC	0.6	4.4	41.1	159.6	37.6
CI + DI + St	0.3	11.9	5.0	3.7	0.2
concrete	97.4	701.3	881.1	190.9	45.7
PVC + HDPE	180.4	2.1	1.0	1.1	0.2

Six WWTPs are connected to the WWC pipe network system as shown in Table 4-2. The main WWTP has 152 million liters per day treatment capacity and is equipped with an incineration plant. The bio-solid sludge from other WWTPs is transported to this treatment facility by trucks for incineration. The initial total capacity of WWTPs is around 90 million m^3/year. On average, 23% of the WWTPs' capacity is reserved for handling surge flows during flood events. The initial average suspended solid concentration of wastewater inflow is recorded as 325 milligram per liter (mg/l).

Table 4-2: WWTP data inventory.

WWTP	***Treatment capacity (million l/day)***	***Current reserve capacity***	***Average inflow suspended solid concentration (mg/l)***
1	29.600	21%	259
2	152.750	24%	264
3	13.620	34%	259
4	28.270	17%	644
5	0.560	30%	207
6	20.700	25%	317

4.2.2.1.2 Finance sector

To achieve financial sustainability, revenue must match expenses. Income is generated from collecting user WWC and WWT fees, development charges, interest earnings, and service connection fees.

The initial user fees for wastewater collection and treatment are \$0.59/m^3 and \$0.50/m^3 respectively to set revenue equal expenses at the start of the model simulation. Development charges are due when permits for construction of new residential buildings or non-residential areas are issued. Table 4-3 shows the initial unit development charges for different types of development used by the City of London, Ontario (2018).

Table 4-3: Initial unit development charges.

Development type	***Charges****	***Unit***
Apartment & Lodging	3706	\$/unit
Townhouse & Semi/Single	5932	\$/unit
Non-residential	38	\$/ft^2

* It is assumed that one fourth of the development charges are allocated for building new treatment plant capacity, and the rest are paid for upgrading or constructing other infrastructure

The connection-service charges are based on water-meter sizes and are collected on a monthly basis. Table 4-4 shows the initial number of meters of different sizes and corresponding monthly service charges.

Table 4-4: Service connection charges and number of meters.

Diameter of water meter (mm)	***15***	***19***	***25***	***40***	***50***	***75***	***100***	***150***	***200***	***250***
Number of meters	106,806	1,975	2,441	877	1,338	50	36	33	8	0
connection charges (\$/month)	27	33	44	74	110	223	477	952	1,546	1,903

Expenses are classified under operational and capital expenditures. Capital activities include the rehabilitation of WWC pipes and construction of new WWTP capacity. The unit costs of ICG5 and ICG4 pipe rehabilitation are considered to be \$1000/meter and \$700/meter, respectively, as reported by Younis (2011). The capital cost for WWTP capacity expansion is considered to be \$3000/m^3 based on guidelines from the City of London, Ontario (2015).

4.2.2.1.3 Consumer sector

The initial population of the studied city is 377,000 people, but this number is assumed to increase by 0.1 % each year. The price elasticity of water demand, which represents the percentage change in water demand per corresponding percentage change in water service fee, is assumed to be a constant -0.35. The initial water demand of residential users is 186 liters per capita per day (LPCD), with the minimum water demand set at 150 LPCD, and the initial annual water demand of non-residential users is 19.75 million cubic meters.

4.2.2.1.4 Environment sector

The direct GHG emission is calculated based on the N_2O, and CH_4 gas emissions from wastewater collection and treatment systems (IPCC 2006). CO_2 emission is not accounted for since it is classified as "biogenic" emission, i.e., it would otherwise have been emitted through natural processes of decay (IPCC 2006). The methane gas emission is considered to be zero as the demotic and industrial wastewater is treated in the centralized treatment systems where secondary-mechanical treatments are applied to remove most organic matter. The nitrous oxide emissions from treatment processes are considered to be four g/person/year by attributing the industrial and commercial discharges to residential users (IPCC 2006).

The indirect GHG emissions are from the production and supply of material and energy resources or from the affected adjacent infrastructure systems. Table 4-5 shows the energy-use rate and GHG emission factors for the processes that are considered in the GHG emission calculation.

Table 4-5: Energy-use data and GHG emission factors.

Energy use of processes that are accounted for in the energy footprint assessment	***Value***	***Unit***	***References***
Life-cycle energy use of PVC pipes manufacturing	75.2	mega joules/kg	(Du, Woods, and Kang 2012)
Life-cycle energy use of water treatment system	2.4	mega joules / m^3	(Racoviceanu et al. 2007)
Energy use of water distribution system	1.224	mega joules / m^3	From data sent by utility
Energy use of WWC system	0.23	mega joules / m^3	From data sent by utility
Life-cycle energy use of wastewater treatment system (including sludge transportation, incineration, and disposal)	1.55	mega joules / m^3	From data sent by the WWTPs
Life-cycle energy use in pipe installation	405	kwh/m	(Prosser, Speight, and Filion 2013)
GHG-emission factors for rehabilitation of ICG4 pipe using trenchless technologies	2^*	kg $CO_{2\ eq.}{}^{**}$ /m	Rehan and Knight (2007)
GHG-emission factors for replacement of ICG5 and new pipes installation using open-cut technologies	64^*	kg $CO_{2\ eq.}$ /m	Rehan and Knight (2007)
GHG emission factor for one kwh electrical energy production and transmission in Ontario	125	g CO_{2eq}/kwh	Sahely et al. 2006

* Daily traffic is assumed to be 3,500 vehicles/day.

** CO_2 eq. unit is used for climate change impact characterization in LCA (ISO-14040 (2006)).

4.3 Strategic asset management scenarios

The base-line asset management scenario is defined based on the acceptable maximum fraction of ICG5 pipe being equal to 10% of the network-length/year, and is commonly employed as a reasonable asset management policy in literature, e.g., Rehan et al. (2015); Rehan et al. (2011b); Rehan et al. (2013a); A. Ganjidoost et al. (2018). An alternative scenario is to keep the ICG5 fraction below the initial 2.8% of network-length/year for the entire life cycle of the asset. This strategy is suggested to maintain the current service level of WWC systems for users and accelerate the rehabilitation and replacement of deteriorated WWC pipes.

The subordinated policy levers, such as the maximum rehabilitation rate, and maximum or minimum user-fee hike rates for WWC and WWT services are adjusted to support the selected strategic decisions. The maximum rehabilitation rates of 1.41% and 1.85% of network length/year are identified by trial and error to keep the ICG5 fractions below the selected 10% and 2.8% thresholds, respectively. The lowest maximum WWC-fee, WWT-fee, and development-charge hike rates are found to be respectively 8.45%, 11.5%, and 12.6% per annum for the base-line scenario, and 12.5%, 3.5%, and 5% per annum for the accelerated rehabilitation scenario. The values of these policy levers are summarized in Table 4-6.

Table 4-6: Estimated policy levers in alternative scenarios.

Policy levers	***Base-line rehabilitation***	***Accelerated rehabilitation***
1- Max. replacement and rehabilitation rate (% of the network length/year)	1.41	1.85
2- Max. allowable WWC fee-hike rate (% per annum)	8.45	12.5
3- Max. allowable WWT fee-hike rate (% per annum)	11.5	3.5
4- Min allowable WWT fee-hike rate (% per annum)	0	0
5- Max allowable development-charge hike rate (% per annum)	12.6	5
6- Min allowable development-charge hike rate (% per annum)	0	0

4.4 Presentation of results

The future behavior of the wastewater collection system and social, finance, and environmental performances of asset management scenarios are projected in this section. Figure 4-1 to Figure 4-11 provide a means of understanding the future trends and forecasting the sustainability outlook of the strategic decisions in asset management planning process.
Figure 4-1, plot (a) and (b) respectively represent the fraction of the ICG5 and ICG4 pipes in each scenario over the 100-year simulation period.

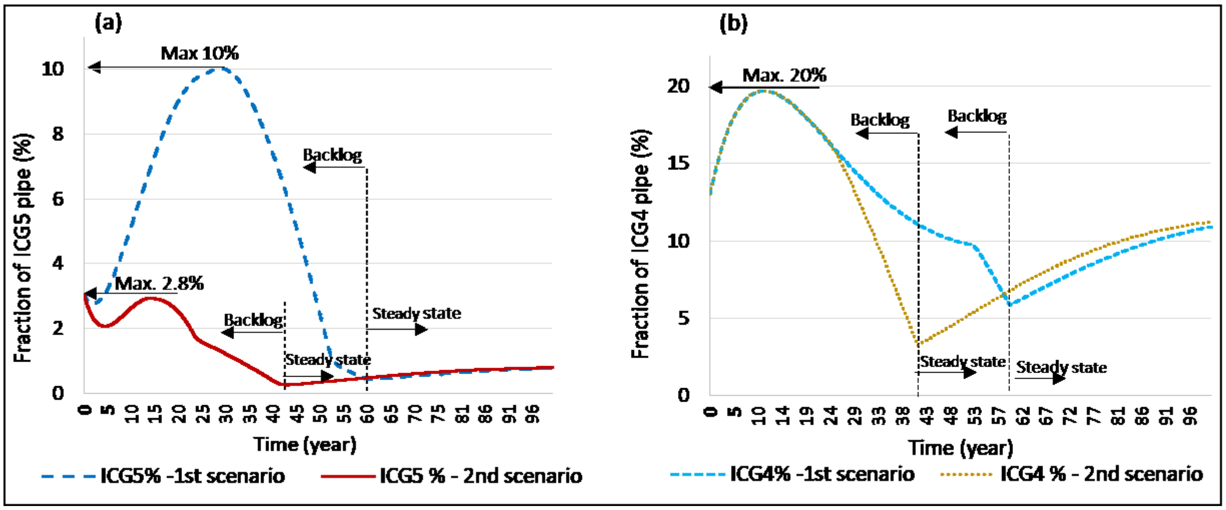


Figure 4-1: a) Fraction of ICG5 pipes, and b) Fraction of ICG4 pipes.

It shows that the adjusted maximum rehabilitation rates of 1.41% and 1.85% (network length/year) suffice to maintain the ICG5 fractions below 10% and 2.8% (network length/year) respectively in the base-line and accelerated-rehabilitation scenarios.

The fraction of ICG5 pipes in the base-line scenario increases to the maximum 10% threshold within 30 years; then, it reduces to lower than the initial 2.8% level after about 50 years. Therefore, users can experience a better than initial-level service only after 50 years subscription to the WWC and WWT services with every-year increased fees. After year 60, the WWC physical sector reaches to a steady state where the total length of CG4 and ICG5 pipes is increasing at the same rate as the rehabilitation rate toward the end of the simulation period.

The ICG5 fraction in the accelerated-rehabilitation scenario will reduce to 2% during the first 5 years and then increase to reach the initial 2.8% level in year 15. In year 25, the fraction of ICG5 pipes are reduced to less than 1.85% of the network length. Therefore, the model embark ICG4 pipes to fill-up the annual rehabilitation capacity. The fraction of ICG4 and ICG5 pipes reach to their lowest level at year 40. After rehabilitation and replacement of ICG5 and ICG4 backlogs, the WWC physical sector reaches to a steady state in year 40.

Figure 4-2 presents the actual rehabilitation rates and related capital expenses for each scenario in plot (a) and (b) respectively. As shown in Figure 4-2, plot (a), the highest rehabilitation rate of 1.85% in the second scenario is achieved after about 15 years and concludes in about year 40, at the onset of the steady-state. In the second scenario, the base-line rehabilitation rate of 1.41% starts from the initial year and continues for about 60 years until it joins the same steady-state of the second scenario.

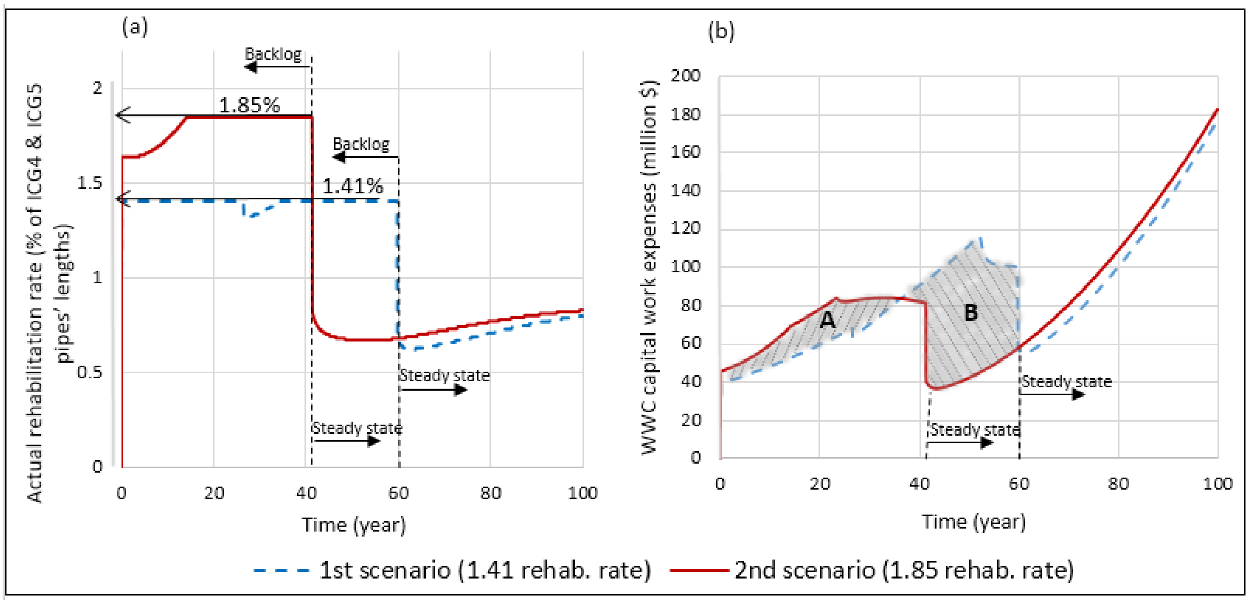


Figure 4-2: a) Actual WWC pipes' rehabilitation rate, and b) Capital work expenses for WWC system.

It should be note that the actual rehabilitation rate depends on the availability of pipes in ICG 5 or ICG4 categories and the existence of a positive funds balance. In Figure 4-2, plot (a), the actual rehabilitation rate in the second scenario is lower than the maximum rehabilitation rate of 1.85 during the first 15 years due to a lack of funds, then it drops to nearly 0.5 % after 40 years when the backlog inventory of ICG 5 and ICG4 pipes are eliminated.

Figure 4-2, Plot (b), shows the WWC pipes' rehabilitation and replacement costs. As expected, the accelerated rehabilitation rate in the first scenario incurs higher capital expenses until about year 35. However, the annual capital expenses for the base-line scenario surpass the annual capital expenses of the second scenario for the next 25 years. The hatched 'A' area represents the additional capital investments used to accelerate the WWC pipes' rehabilitation and replacement in the second scenario. It is evident that this additional capital investment is smaller than the required capital expenses in the base-line scenario which is the hatched 'B' area.

The annual total wastewater-inflow volume and the built treatment plants capacities in each scenario are presented in Figure 4-3 in plot (a) and (b) respectively. The annual wastewater volume in the base-line scenario increases for about 30 years until it reaches its maximum level of 104 million m^3/day. In the second scenario, the annual wastewater volume will not exceed the initial level until year 80. In Figure 4-3, plot (a), the additional wastewater volume that requires building WWTP capacity in the second scenarios is hatched ('A' area).

The built WWT capacity presented in Figure 4-3 in plot (b) corresponds with the WWTP's annual wastewater-inflow volume. In the first scenario, the increased wastewater-inflow volume imposes the need to build additional treatment capacities from the initial years until year 30 (when the wastewater volume is at its maximum level), whereas in the second scenario, this need does not arise until about year 80.

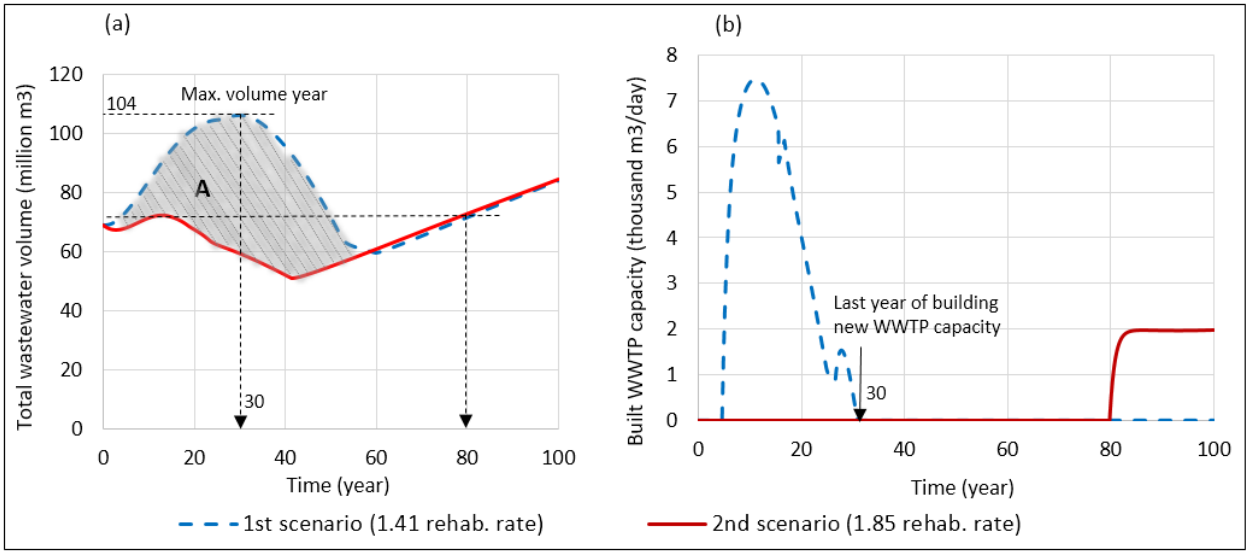


Figure 4-3: a) WWTP wastewater-inflow volume and b) Built WWTP capacity.

The WWTP's capacity is required to treat the sewage generated by residential and non-residential users, as well as the extraneous inflow and infiltration (I&I) the WWC pipe network system. Figure 4-4 demonstrate the proportion of each element in the WWTP's wastewater-inflow volume.

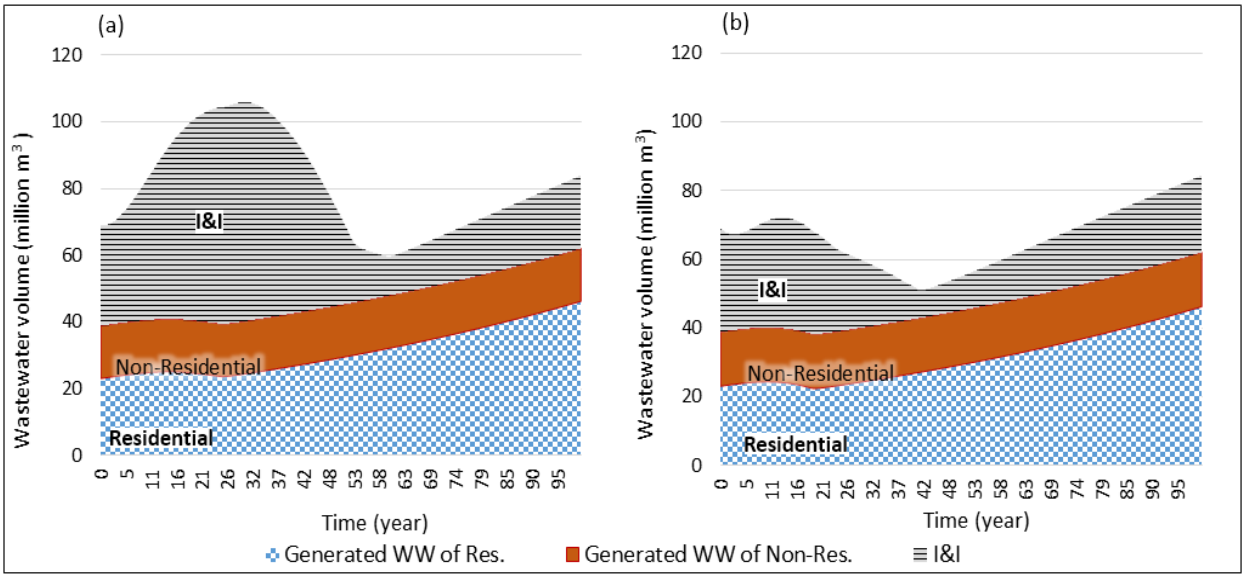


Figure 4-4: Proportion of I&I and generated sewage volumes in a) the 1st scenario with 1.41% rehabilitation rate and b) the 2nd scenario with 1.85% rehabilitation rate.

Comparing the disaggregated wastewater volumes in Figure 4-4 confirm that the main difference between the WWTP's wastewater-inflow volume originates from the differences in I&I volume. The total extraneous I&I flow volume in the base-line scenario, presented in plot (a), is about 1.5 billion m3 higher than the I&I flow in the second scenario.

The volumes of wastewater generated by residential and non-residential users are relatively identical in both scenarios, and water conservation has a negligible impact on total wastewater-flow volumes at WWTP facilities. The volume of residential users' generated sewage increases only due to the population growth which constitute the largest share of the total wastewater volume at nearly the second half of the asset service life. It can be concluded that the extraneous I&I flow volume impose building extra wastewater treatment capacity in the first scenario in about first 35 years (Figure 4-3, plot (a)); whereas, the need for building WWTP capacity in the second scenario derived from the population growth and generated sewage volume by residential users after 80 years.

Figure 4-5 shows the total user fee in plot (a) and the water demands in plot (b) for residential users. The user fees are presented based on the present dollar value. The user fee in the first scenario increases to reach its peak value of 3.5 $/m^3 in year 50, whereas in the first scenario, the user fee reaches its highest value, 3.1 $/m^3, in about year 20.

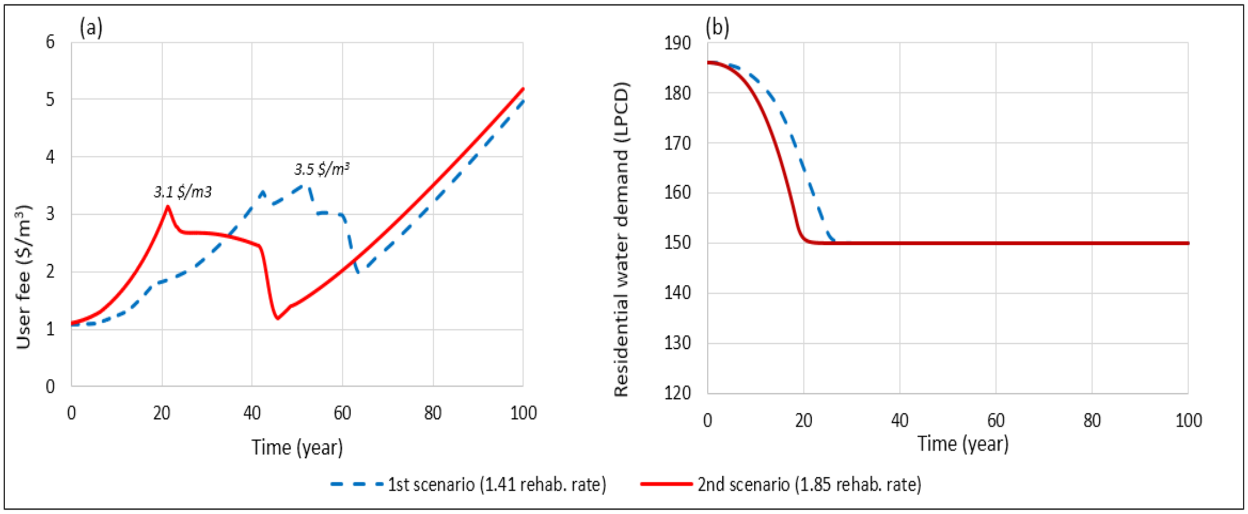


Figure 4-5: a) Residential user fees and b) Residential water demand.

Because the user fees increase in both scenarios, residential users reduce their water demand to minimum level of 150 liter per capita per day (lpcd), as presented in Figure 4-5, plot (b). The minimum water demand level will be reached about 5 years earlier in the second scenario than in the first. The lowered water demand level is maintained as residents adopt their water use behavior for the rest of the asset-management life cycle

Figure 4-6 presents the disaggregate WWT and WWC fees for residential users in each scenario. Comparing the WWC and WWT fees highlights the significance of WWC fees in user-fee variations. In the first scenario, Figure 4-6, plot (a), the contribution of WWT fees is significant for the first 20 years and then starts to diminish over time. In the second scenario, Figure 4-6, plot (b), the WWT fee contribution decreases from the beginning, up to the end of the simulation when the user fees reach about their maximum, 5 $/m^2, in both scenarios.

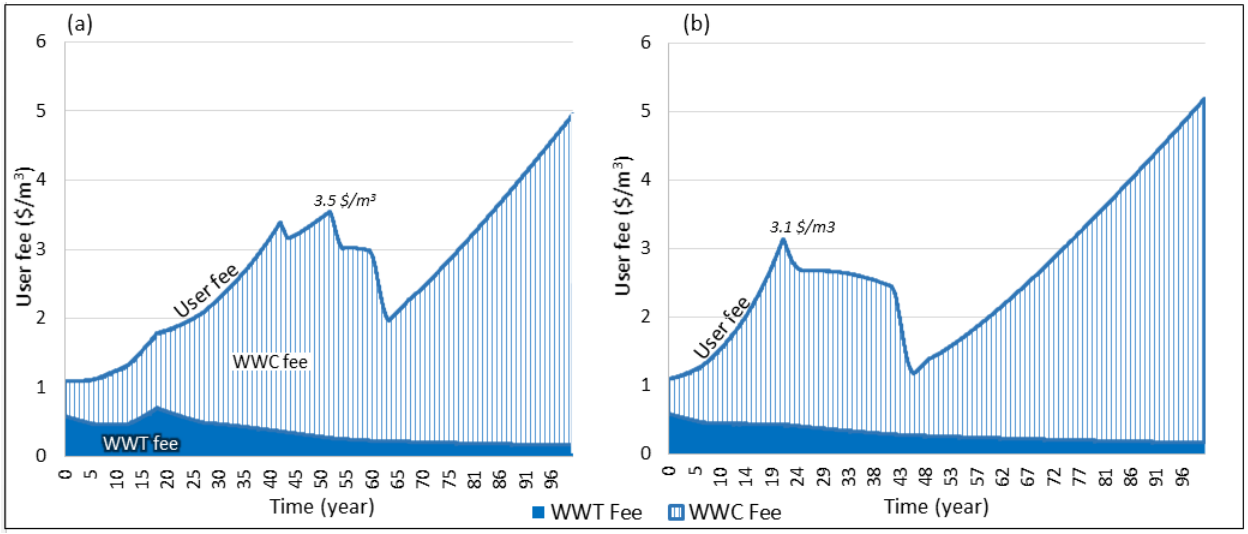


Figure 4-6: Proportion of WWT and WWC fees in annual user-fee results for a) the 1st scenario with1.41% rehabilitation rate and b) the 2nd second scenario with 1.85% rehabilitation rate.

Figure 4-7 shows the changes in development charges based on the present dollar value.

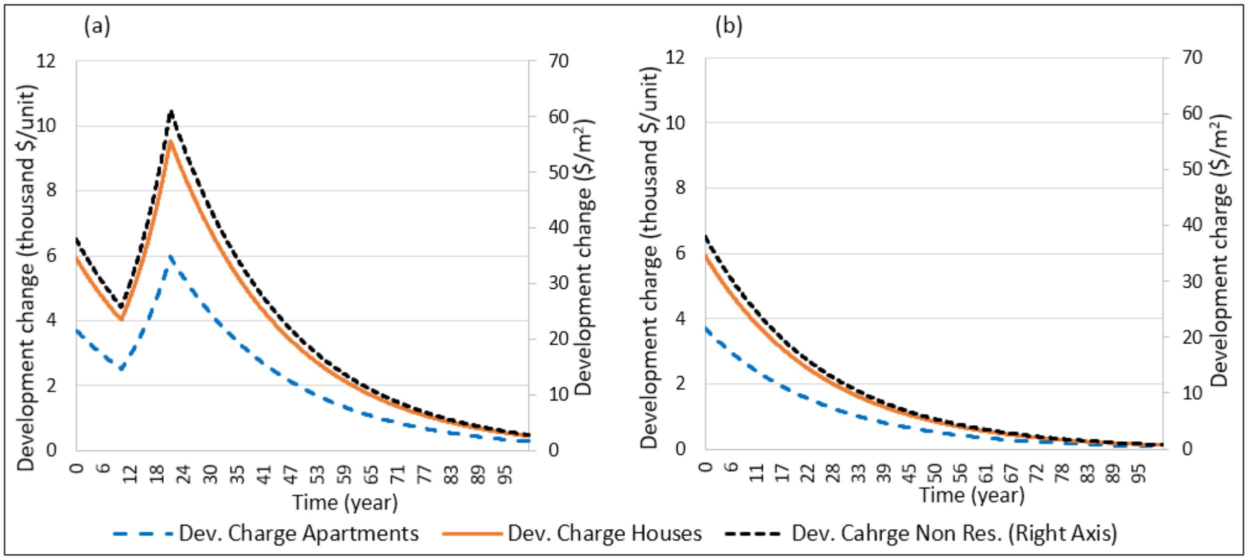


Figure 4-7: Development-charges in a) the 1st scenario with1.41% rehabilitation rate, and b) the 2nd scenario with1.85% rehabilitation rate.

In the first scenario, the development charges increase to their highest value in year 24, and reach approximately \$5000 for new apartments, \$10,000 for new houses, and \$60/m² for new non-residential buildings. In contrast, the development charges in the second scenario continuously depreciate from the beginning, and reach less than \$1000 for new residential units and \$5/m^2 for non-residential developments in year 50.

The annual energy-use and GHG emission results are presented in Figure 4-8, plot (a) and Figure 4-8, plot (b), respectively. The annual energy-use in the first scenario is slightly lower than that in the second scenario until about year 10, and it reaches 500 gigajoules/yr in about year 35. The energy-use in the second scenario reaches about 450 gigajoules/yr in about year 15 and starts to decline to as low as 350 gigajoules/yr in the second scenario in about year 40. A similar comparison is attainable for the annual GHG emission results. The annual total GHG emission in the first scenario rises to above 8.5 million tones CO_2 eq. in about year 35, whereas it drops to below 5.5 million tones CO_2 eq. in the second scenario in about year 40. Hatched area 'A' and 'B' represent the additional total energy use and GHG emissions result from taking the 1.41 rehabilitation rate strategy in the baseline scenario.

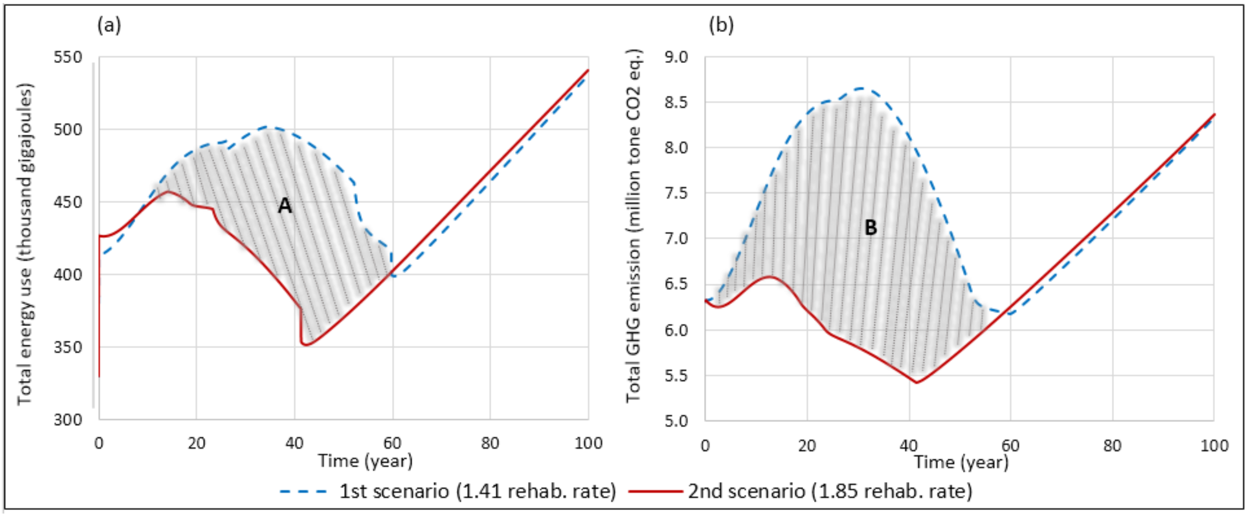


Figure 4-8: a) Total energy use and b) Total GHG emission results.

The contributions of different processes associated with the total GHG emissions in the first and second scenarios are presented in Figure 4-9, plot (a) and plot (b), respectively. The main variations in GHG emissions in both scenarios result from the variation of GHG emissions from WWTP processes, and correlate to the variations in I&I volume presented in Figure 4-4.

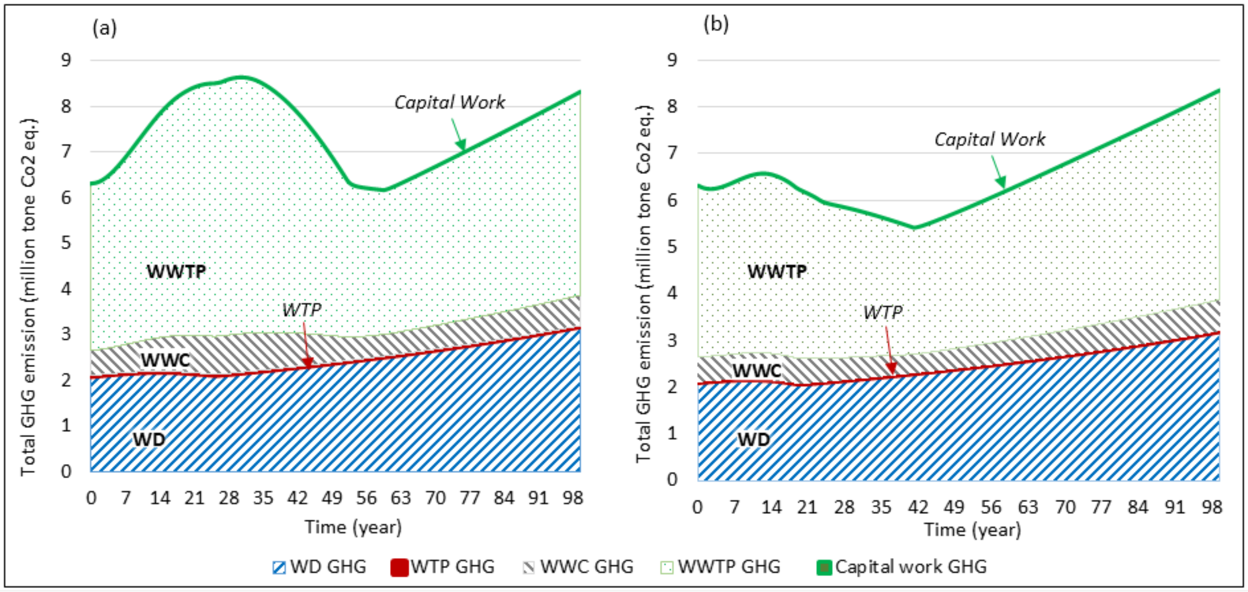


Figure 4-9: Proportion of GHG emission from different sources in total annual GHG emissions based on data presented in Table 4-5 for a) the 1st scenario with 1.41% rehabilitation rate, and b) the 2nd scenario with 1.85% rehabilitation rate.

Aggregated GHG emission results, presented in Figure 4-10, illustrate that the largest GHG emissions are attributed to the water distribution and WWTP processes; whereas, the GHG emissions from capital work and water treatment plant (WTP) processes have negligible contribution to the total GHG emissions.

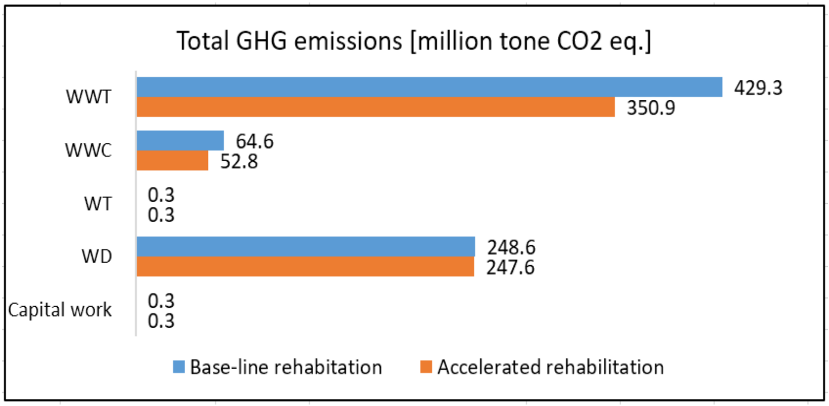


Figure 4-10: Total GHG emissions from different processes.

Figure 4-11 is presented to compare the total annual operational and capital expenses of WWC pipe network and treatment plant systems when base-line and accelerated rehabilitation strategies are implemented. The capital expenses of WWC systems are the main variable in asset management costs in both scenarios. For the first 40 and 57 years of the asset life-cycle, respectively in the first and second scenarios, capital expenses are the highest cost to the WWC and WWT systems. Later, the operational expenses of WWC systems become more significant than the capital expenses toward the end of the asset's service life.

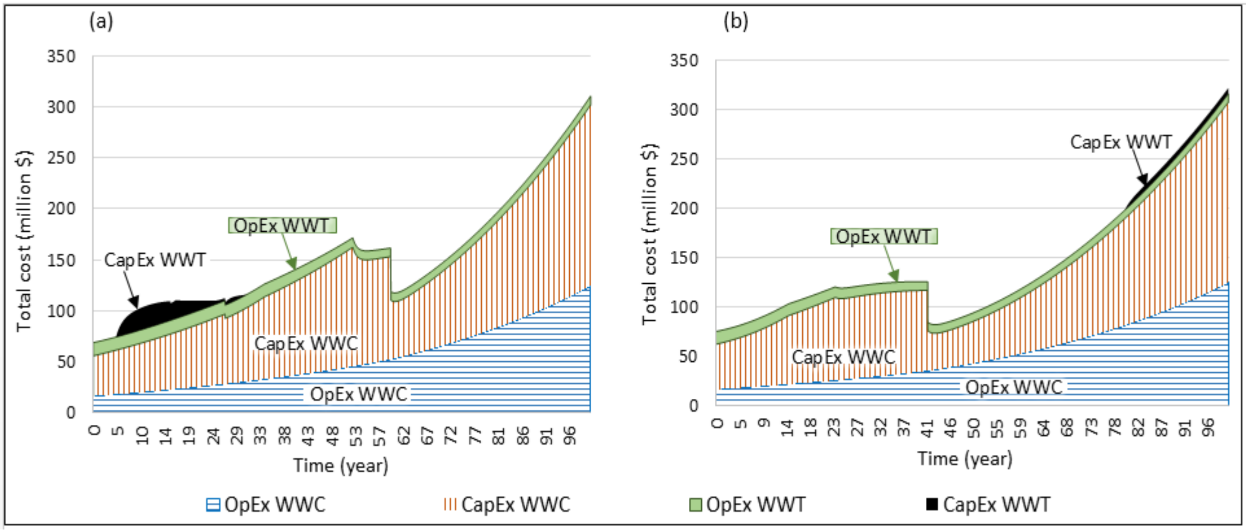


Figure 4-11: Proportion of operational and capital expenses in total annual expense for a) 1st scenario with 1.41% rehabilitation rate and b) 2nd scenario with 1.85% rehabilitation rate.

As presented in Figure 4-12, the differences between the life cycle costs of the two scenarios are mainly due to the differences in WWC and WWT capital expenses, which are denoted as WWC_CapEx and WWT_CapEx in Figure 4-12, respectively.

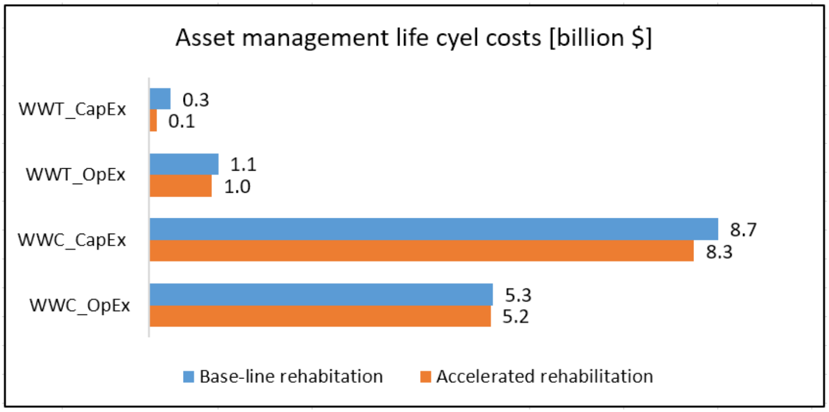


Figure 4-12: Asset management life cycle cost components.

4.5 Summary of results and discussion

The total cost of the WWC and WWT services for a residential user, total cost of asset management activities for the municipality, and the total GHG emissions from the WWC and other affected infrastructure systems are calculated using Equations (4.1), (4.2), and (4.3), respectively. These three indicators are employed to evaluate the social, financial, and environmental sustainability impacts from implementing the proposed strategic decisions on a WWC pipe network system.

$$User\ cost = \sum_{t=1}^{t=100} \big(WWC\ fee\ (t) + WWT\ fee\ (t)\big) \times\ metered\ water\ (t) \tag{4.1}$$

where

- t $[year]$ represent the current time;
- $Usercost[\$/year]$ is the cost of WWC and WWT service for a residential user in 100 years;
- $WWC\ fee(t)$ $[\$/m^3]$ is the WWC fee paid by a residential user in year t;
- $WWT\ fee(t)$ $[\$/m^3]$ is the WWT fee paid by a residential user in year t;
- $metered\ water(t)$ $[M^3/year]$ is the volume of water used by a residential user in year t;
- 100 $[year]$ is the simulation period, which captures the life cycle of the assets.

$$City\ of\ London\ cost = \sum_{t=1}^{t=100} [\big(WWC\_OpEx(t) + WWC\_CapEx(t)\big) + (WWT\_OpEx(t) + WWT\_CapEx(t)] \tag{4.2}$$

where

- t $[year]$ represent the current time;
- $City\ of\ London\ cost$ $[\$/year]$ is the cost of asset management operational and capital activities for the integrated WWC and WWT systems;
- 100 $[year]$ is the simulation period, which captures the life cycle of the assets;
- WWC_OpEx $[\$/year]$ represents the annual operational expenses for WWC systems in year t;
- WWC_CapEx $[\$/year]$ represents the annual capital-work expenses for rehabilitation and replacement of WWC pipes in year t;

- WWT_OpEx $[\$/year]$ represents the annual operational expenses for WWT systems in year t;
- WWC_CapEx $[\$/year]$ represents the annual capital-work expenses for construction of new WWTP capacities in year t.

$$LC\_GHG\ emisison\ = \sum_{t=0}^{t=100} WTP\_GHG(t) + WD\_GHG(t) + WWC\_GHG(t) + WWTP\_GHG(t) + CapWork\_GHG(t) \quad (4.3)$$

where

- t $[year]$ represent the current time;
- $LC\_GHG\ emission[CO_2]$ represents the total GHG emissions from implementing asset management strategies in each scenario for the 100 years simulation period;
- WT_GHG $[CO_2]$ is the annual GHG emissions from the water treatment plant system in year $[t]$;
- WD_GHG $[CO_2]$ is the annual GHG emissions from the water distribution in year $[t]$;
- WWC_GHG $[CO_2]$ is the annual GHG emissions from WWC system in year $[t]$;
- WWT_GHG $[CO_2]$ is the annual GHG emissions from WWTP system in year $[t]$;
- $CapWork\_GHG[CO_2]$ is the GHG emissions from rehabilitation and replacement of WWC pipes in year $[t]$.

The calculated result for each sustainability indicator is presented in Table 4-7.

Table 4-7: Average annual cost for different scenarios and stakeholders.

Bottom lines	***Base-line rehabilitation***	***Accelerated rehabilitation***
Total cost to a residential user (thousand $)	12.1	11.7
Total cost to the municipality (billion $)	14.2	13.8
Total GHG emission (million tone CO_2 eq.)	743.2	651.9

The results show that the cost for resident users and for the municipality will be lowered if the accelerated-rehabilitation strategy is employed by the wastewater utility. This accelerated rehabilitation strategy also improves the environmental footprint of the asset management activities in terms of GHG emissions.

Figure 4-13 present the affordability results for residential service users. The affordability or bill burden, which represents the percentage of annual average household income paid for wastewater collection and treatment services, stays below the 2.5 % affordability threshold (EPA 2002) until year 80 under both scenarios. In the second scenario, this social sustainability indicator stays below 1% for about 60 years until it increases to nearly 5% at the end of the simulation period. In contrast, in the first scenario, affordability passes 1% after 35 years and increases steadily each year until it reaches the same trend as the second scenario in about year 65. The average affordability ratio for the first and second scenarios are 1.52% and 1.49% respectively.

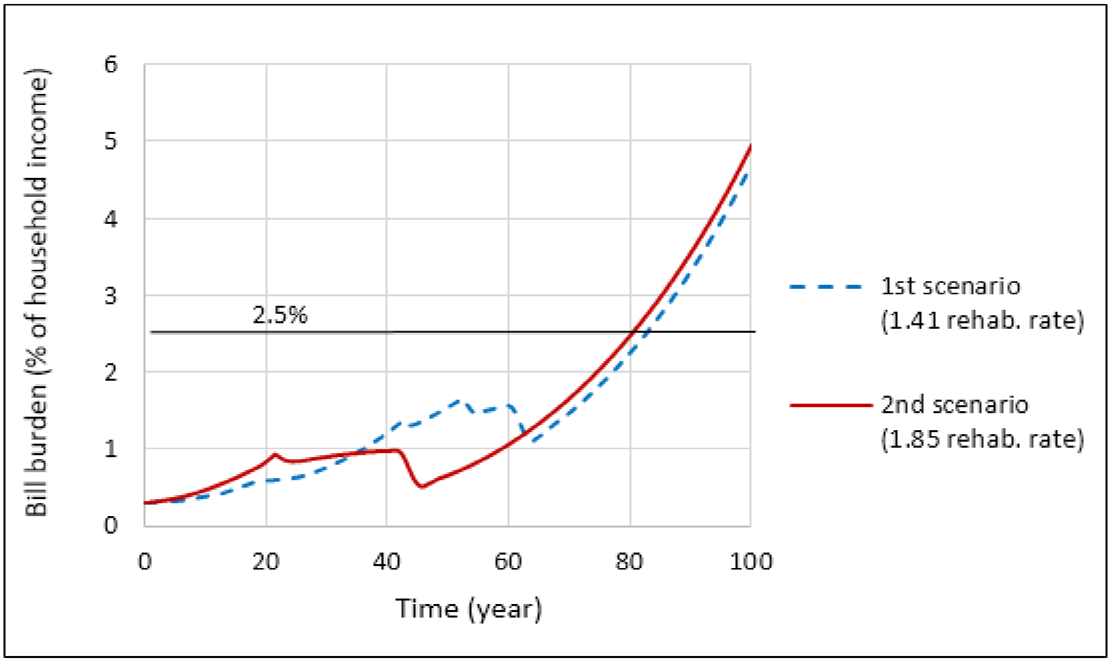


Figure 4-13: Affordability of wastewater collection and treatment services for residential users.

4.6 Conclusions

Inflow and infiltration considered excessive when

- It causes overflow or bypass events;
- The cost of its transportation and treatment exceeds the cost of its elimination;
- It causes health and environmental risks;
- It causes building new WWTP capacities. (US-EPA 2014)

The case study results shown that I&I is excessive as the cost of I&I transportation and treatment in the first scenario exceeds the investment cost to accelerate the rehabilitation of ICG4 and ICG5 pipes. Moreover, the future WWTP capacity requirement mainly result from the I&I increases which cause significant GHG emissions.

Comparing the social, environmental, and economic cost results show that a more cost-effective solution would be reached if a higher rehabilitation rate policy is considered for the presented case-study WWC system. The accelerated rehabilitation strategy in the second alternative asset management plan will have a lower financial cost, without the need to compromise social or environmental values in achieving a sustainable state.

This study highlights the implications of integrating asset management of wastewater collection and treatment systems. Applying such an integrated model will help decision makers to evaluate the behavior of interrelated wastewater-collection and -treatment systems, and find synergistic cost-saving opportunities while taking decisions on when, where, and how to invest in infrastructure upgrading and installation.

This study has limitations in evaluating alternative financial management strategies. A more complete assessment would include other financial approaches, such as the borrowing and capital reserving strategies developed and modeled by Rehan et al. (2011), to develop other asset management plan alternatives. Moreover, a complete sustainability assessment will embrace evaluation of more environmental and social indicators related to the asset management plans at the strategic level.

Chapter 5

Conclusions, contributions, and future research

5.1 General conclusions

Specific conclusions for various aspects of this research are provided in Chapters 2 to 4 under their respective conclusion sections. A general summary is presented below.

The proposed sustainability assessment framework presents the sustainability outlook of various strategic decisions for the asset management of water and wastewater infrastructure systems. The integration of life-cycle thinking and system dynamic perspectives within the infrastructure asset management planning context is the most important feature of the proposed sustainability assessment framework. The scope of the assessment acknowledges three areas of sustainability: social, environmental, and economic sustainability. The boundary of the system is broadened to embrace upstream and downstream systems affected by strategic decisions in wastewater asset management. This wide scope enables the assessment to capture the non-linearity, variability, and variety of drivers and feedback that affect the sustainability of the entire wastewater infrastructure system represented by both collection pipes and treatment plants. The time-frame of the assessment includes the life cycle stages of both the collection pipes and treatment plant systems in order to avoid sub-optimization or problem-shifting pitfalls.

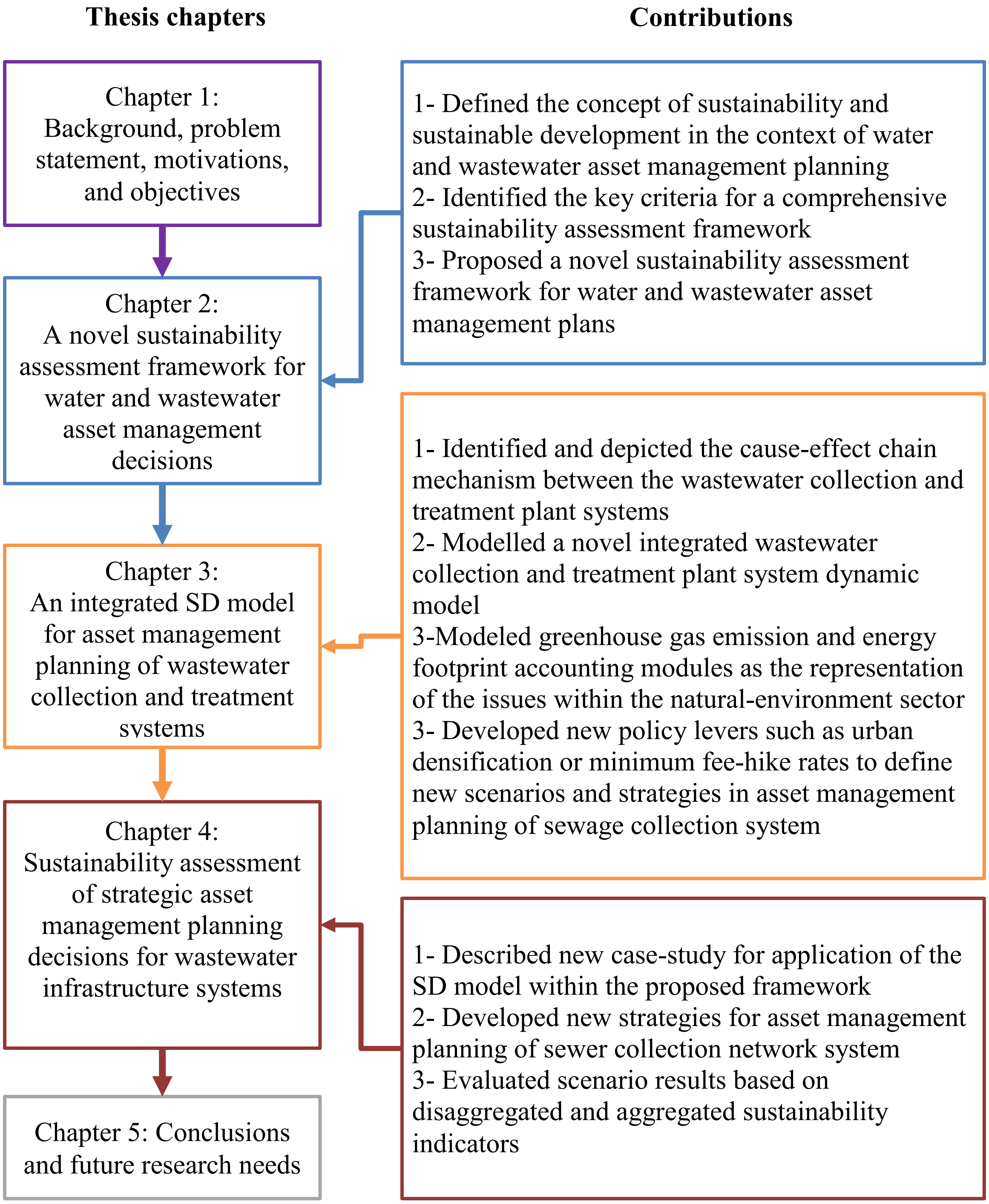
The social, environmental, and financial sustainability of the combined waste water pipe and treatment plant infrastructure assets are evaluated under the condition of population growth and urban densification, as factors that drive change in the sustainability performance and asset management of these interconnected systems over their lifecycles. The utility of the proposed framework is evaluated, both from the normative view on sustainability assessment as well as from empirical research, using a case-study. Moreover, the case-study demonstrates the applicability of the proposed framework for optimizing the decision making process when developing socially acceptable, environmentally friendly, and financially viable asset management plans.

5.2 Contributions

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

1. A novel sustainability assessment framework is developed to evaluate strategic decisions for the social, environmental and financial performance components for asset management planning for water infrastructure systems.
2. A new causal loop diagram is presented to provide a qualitative understanding of the interrelations and feedback mechanisms between wastewater collection and treatment plant systems, in the context of social, environmental, and economic sustainability.
3. A new system dynamic model is constructed that integrates wastewater-collection and treatment-plant systems, and is used to parametrize and quantify the processes identified in the causal loop diagram.
4. The utility of the system dynamics model is demonstrated using a case-study to develop a strategic asset management strategy for the sustainable rehabilitation and replacement of an existing wastewater collection system, in conjunction with the operation and expansion of the adjoining wastewater treatment plant systems.

Figure 5-1 presents the specific contributions being made in each chapter of this thesis.



Thesis chapters

Chapter 1:
Background, problem statement, motivations, and objectives

Chapter 2:
A novel sustainability assessment framework for water and wastewater asset management decisions

Chapter 3:
An integrated SD model for asset management planning of wastewater collection and treatment systems

Chapter 4:
Sustainability assessment of strategic asset management planning decisions for wastewater infrastructure systems

Chapter 5: Conclusions and future research needs

Contributions

1- Defined the concept of sustainability and sustainable development in the context of water and wastewater asset management planning
2- Identified the key criteria for a comprehensive sustainability assessment framework
3- Proposed a novel sustainability assessment framework for water and wastewater asset management plans

1- Identified and depicted the cause-effect chain mechanism between the wastewater collection and treatment plant systems
2- Modelled a novel integrated wastewater collection and treatment plant system dynamic model
3-Modeled greenhouse gas emission and energy footprint accounting modules as the representation of the issues within the natural-environment sector
3- Developed new policy levers such as urban densification or minimum fee-hike rates to define new scenarios and strategies in asset management planning of sewage collection system

1- Described new case-study for application of the SD model within the proposed framework
2- Developed new strategies for asset management planning of sewer collection network system
3- Evaluated scenario results based on disaggregated and aggregated sustainability indicators

Figure 5-1: Contributions made in each chapter.

5.3 Direction for future research

The most important contribution of this research is that it presents an innovative framework for life cycle sustainability assessment of strategic decisions in the asset management of water and wastewater infrastructure systems. However, the application of this framework can be extended to other municipal infrastructures systems such as roads and buildings. Supported by the same conceptual framework, the sustainability assessment of wastewater asset management plans can be further extended by including of the following ideas:

1. The system-change drivers that are investigated in the SD model are limited to pipe aging, population growth and urban densification. The present SD model can be extended to include other drivers such as water resource availability, which is particularly important for municipalities experiencing water resource scarcity.
2. The present SD model is constructed to study the interaction and feedbacks between WWC and WWTP systems. However, Rehan et al. (2015) apply a precursor SD model to an urban water distribution system, while Ganjidoost (2016) applies an analogous model to examine the interaction between WD and WWC pipe network systems. Figure 5-2 proposes a complete SD model for the entire urban water cycle, which includes consideration of interactions of WTP with WD and WWTP systems.

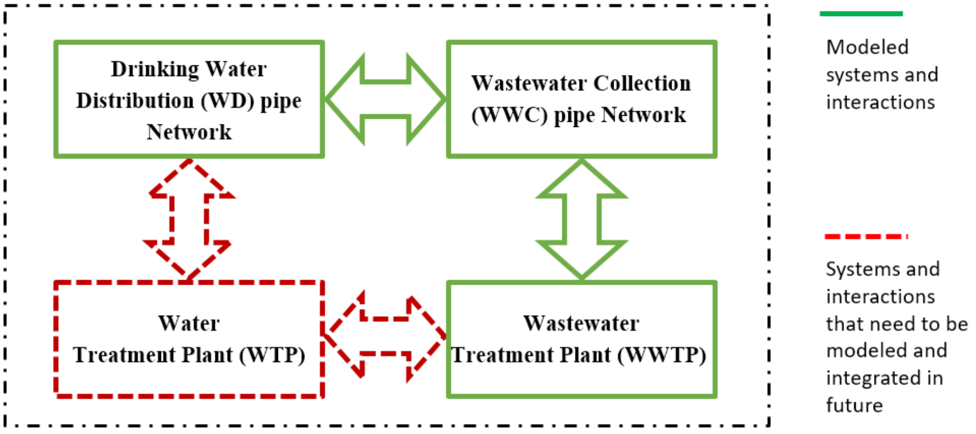


Figure 5-2: Future SD model development of urban water cycle.

3. Water demand for non-residential users is assumed to be price-inelastic within the present SD model. For a more-realistic representation of the consumer sector, specific user fees and price elasticity factors should be developed for industrial, commercial, and institutional users, to thereby, revise the water-demand-prediction component of the consumer sector.
4. The scope of the environmental sector can be expanded and refined by identifying and modeling additional environmental footprints, such as the water footprint, that are relevant to the present scope of the strategic sustainability assessment.
5. The developed framework employs the SD modeling tool to forecast the life cycle sustainability performance of the infrastructure systems. This predictive analysis can help decision makers to pose and answer 'what', 'when', and 'why' questions regarding the future sustainability performance of infrastructure systems. However, a higher level of analysis involves decision makers postulating 'how' questions. These follow naturally from 'what', 'when', and 'why', but would involve a level of optimization to be integrated into the SD model to develop appropriate values of policy levers.
6. The scope of the SD model can be extended by developing and employing performance benchmark-indicators in the manner developed by Ganjidoost et al. (2018).

List of References

(CSCE). 2013. “CSCE ’ s Vision 2020.” https://csce.ca/wp-content/uploads/2013/10/CSCE-Vision-business-plan.pdf.

(IPCC), Intergovernmental Panel on Climate Change. 2006. “Chapter 6 Wastewater Treatment and Discharge.” In .

Adeniran, Ezekiel A., and Olufemi A. Bamiro. 2010. “A System Dynamics Strategic Planning Model For A Municipal Water Supply Scheme.” *Production*, 1–14.

Balmér, Peter, and Bengt Mattson. 1994. “Wastewater Treatment Plant Operation Costs.” *Water Science and Technology* 30: 7–15.

Beheshti, Maryam, and Sveinung Sægrov. 2018. “Sustainability Assessment in Strategic Management of Wastewater Transport System: A Case Study in Trondheim, Norway.” *Urban Water Journal* 15 (1). Taylor & Francis: 1–8. doi:10.1080/1573062X.2017.1363253.

Biachia, Carmine, and Giovan Battista Montemaggiore. 2008. “A System Dynamics-Based Simulation Experiment for Testing Mental Model and Performance Effects of Using the Balanced Scorecard.” *System Dynamics Review, Vol. 25 No.1* 24 (2): 175–213. doi:10.1002/sdr.

British Standard Institute. 2008. “PAS 55-1.” In *Pubmicly Available Specification*.

Brundtland, Gru, Mansour Khalid, Susanna Agnelli, Sali Al-Athel, Bernard Chidzero, Lamina Fadika, Volker Hauff, et al. 1987. “Our Common Future ('Brundtland Report’).”

Canadian Infrastructure Report Card, 2012. 2012. “Canadian Infrastructure Report Card, 2012.” Vol. 1.

Carson, Rachel. 1962. *Silent Spring*. Boston ;Cambridge Mass.: Houghton Mifflin ;;Riverside Press.

Cashman, Sarah., Anthony. Gaglione, Janet. Mosley, Lori Weiss, Troy R. Hawkins, Nick J.

Ashbolt, Jennifer Cashdollar, Xiaobo Xue, Cissy Ma, and Sam Arden. 2014. *Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Wastewater Treatment*.

Changsirivathanathamrong, A, S Moore, and K Linard. 2007. "Integrating System Dynamics with LCA : A Framework for Improved Policy Formulation and Analysis." Modelling and Simulation Society of Austral- ia and New Zealand (MSSANZ).

Chung, G., K. Lansey, P. Blowers, P. Brooks, W. Ela, S. Stewart, and P. Wilson. 2008. "A General Water Supply Planning Model: Evaluation of Decentralized Treatment." *Environmental Modelling and Software* 23 (7): 893–905. doi:10.1016/j.envsoft.2007.10.002.

CICA. 2007. *Guide to Accounting for and Reporting Tangible Capital Assets*. Public Sector Accounting Group of the Canadian Institute of Chartered Accountants (CICA).

City of London. 2018. "Development Charges." Accessed October 5. https://www.london.ca/business/Resources/Development-Financing/Pages/Development-Charges.aspx.

———. 2015. "2015 Wastewater Council Approved Budget." London.

City of Toronto. n.d. "Annual Wastewater Treatment Plant Reports." http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=da8807ceb6f8e310VgnVCM10000071d60f89RCRD&vgnextchannel=6b2655b89b6fe310VgnVCM10000071d60f89RCRD.

Clarke, K F D a - 1994. 1994. "Sustainability and the Water and Environmental Manager." *Journal of the Institution of Water and Environmental Management* 8: 1–9 ST– Sustainability and the water and environ.

Das, Nhakta Kabi, Manas Bandyopadhyay, and Pratap K. J. Mohapatra. 1995. "Model for Activated Sludge.Pdf." *System Dynamics* 2.

DeZellar, Jeffrey T., and Maier Walter J. 1980. "Effects of Water Conservation on Sanitary

Sewers and Wastewater Treatment Plants.” *Water Pollution Control Federation* 52 (1): 76–88.

Du, Fei, Gj Woods, and Doosun Kang. 2012. “Life Cycle Analysis for Water and Wastewater Pipe Materials.” *Journal of …*, no. May: 703–11. doi:10.1061/(ASCE)EE.1943-7870.0000638.

Ehrlich, Paul R. 1971. *The Population Bomb*. Buccaneer Books.

Elkington, John. 1994. “Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development.” *California Management Review* 36 (2): 90–101. doi:10.2307/41165746.

Environment Canada. 2011. “2011 Municipal Water Use Report.” doi:En11-2/2009E-PDF Information.

Environmental Economics Advisory Committee of the EPA Science Advisory. 2002. “Affordability Criteria for Small Drinking Water Systems : An EPA Science Advisory Board Report.”

European Environment Commission. 2007. “Terms and Definitions of the Urban Waste Water Treatment.” Brusseles.

FCM. 2018. “Municipalities for Climate Innovation Program (MCIP).” Accessed May 25. https://fcm.ca/home/programs/municipalities-for-climate-innovation-program/municipalities-for-climate-innovation-program.htm.

Federation of Canadian Municipalities. n.d. “How to Develop an Asset Management Policy, Strategy and Governance Framework: Set up a Consistent Approach to Asset Management in Your Municipality.”

———. 2017. “Leadership in Asset Management Program.” https://fcm.ca/home/programs/green-municipal-fund/resources-and-programs/leadership-in-asset-management-program.htm.

Felio, Guy, and Zoubir Lounis. 2009. “Model Framework for Assessment of State, Performance, and Management of Canada’s Core Public Infrastructure.”

Finnveden, Göran, and Åsa Moberg. 2005. “Environmental Systems Analysis Tools – an Overview.” *Journal of Cleaner Production* 13 (12): 1165–73. doi:10.1016/j.jclepro.2004.06.004.

Fraas, Arthur G., and Vincent G. Munley. 1984. “Municipal Wastewater Treatment Cost.” *Journal of Environmental Economics and Management* 11 (28–38). doi:10.1142/9789814327701_0027.

Ganjidoost, A., M.A. Knight, A.J.A. Unger, and C.T. Haas. 2018. “Benchmark Performance Indicators for Utility Water and Wastewater Pipelines Infrastructure.” *Journal of Water Resources Planning and Management* 144 (3). doi:10.1061/(ASCE)WR.1943-5452.0000890.

Ganjidoost, Amin. 2016. “Performance Modeling and Simulation for Water Distribution and Wastewater Collection Networks.” University of Waterloo.

Ganjidoost, Amin, Carl Haas, Mark Knight, and Andre Unger. 2015. “A System Dynamics Model for Integrated Water Infrastructure Asset Management.” *Proceedings of the 33rd International Conference of the System Dynamics Society* This paper (2012): 1–16.

Gasparatos, Alex, and Anna Scolobig. 2012. “Choosing the Most Appropriate Sustainability Assessment Tool.” *Ecological Economics* 80 (August). Elsevier B.V.: 1–7. doi:10.1016/j.ecolecon.2012.05.005.

Gasparatos, Alexandros. 2010. “Embedded Value Systems in Sustainability Assessment Tools and Their Implications.” *Journal of Environmental Management* 91 (8). Elsevier Ltd: 1613–22. doi:10.1016/j.jenvman.2010.03.014.

Gillot, S, B De Clercq, F Defour, K Gernaey, P Vanrolleghem, U Jeppsonn, J Carstensen, B Carlsson, and G Olsson. 1999. “Optimization of Wastewater Treatment Plant Design and Operation Using Simulation and Cost Analysis.” In *WEF Conference and Exposition*, 9–13.

Goldsmith, Edward. 1972. *Blueprint for Survival*. Houghton Mifflin.

Government of Canada. 2008. *Federal Sustainable Development Act*. Canada.

———. 2016. "Federal Sustainable Development Strategy." http://fsds-sfdd.ca/index.html#/en/goals/.

Government of Ontario. 2018. "Development Charges Act, 1997, Chapter 27." Accessed October 5. https://www.ontario.ca/laws/statute/97d27.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. 2014. "Recommended Standard for Wastewater Facilities." Albsny,N.Y.

Grigg, Neil S., and Maurice.C. Bryson. 1975. "Interactive Simulation for Water Dynamics." *Journal of the Urban Planning and Development Division* 101 (1): 77–92.

H. Meadows, Donella, Dennis L. Meadows, Jorgen Randers, and William W. Behrens. 1972. "The Limits to Growth." *A Report for the Club Of Rome's Project on the Predicament of Mankind*. doi:10.1111/j.1752-1688.1972.tb05230.x.

Halog, Anthony, and Yosef Manik. 2011. "Advancing Integrated Systems Modelling Framework for Life Cycle Sustainability Assessment." *Sustainability* 3 (12): 469–99. doi:10.3390/su3020469.

Hellström, Daniel, Ulf Jeppsson, and Erik Kärrman. 2000. "A Framework for Systems Analysis of Sustainable Urban Water Management." *Environmental Impact Assessment Review* 20 (3): 311–21. doi:10.1016/S0195-9255(00)00043-3.

Hernandez-Sancho, F., M. Molinos-Senante, and R. Sala-Garrido. 2011. "Cost Modelling for Wastewater Treatment Processes." *Desalination* 268 (1–3). Elsevier B.V.: 1–5. doi:10.1016/j.desal.2010.09.042.

Infrastructure Canada. 2018. "2014-2015 Report on Plans and Priorities Section 1." Accessed October 11. http://www.infrastructure.gc.ca/pub/rpp/2014-15/2014-01-eng.html.

ISO-14040. 2006. *ISO-14040 Environmental Management — Life Cycle Assessment — Principles and Framework*. 2nd ed. Vol. 2006.

ISO. 2014. "ISO 55000| Assessments and Road Mapping Services." https://www.assetmanagementstandards.com/assessments-roadmapping/.

Marleni, N., S. Gray, A. Sharma, S. Burn, and N. Muttil. 2015. "Impact of Water Management Practice Scenarios on Wastewater Flow and Contaminant Concentration." *Journal of Environmental Management* 151. Elsevier Ltd: 461–71. doi:10.1016/j.jenvman.2014.12.010.

Min, Kyungnan, and Steven A Yeats. 2011. "Water Conservation Efforts Changing Future Wastewater Treatment Facility Needs." *Flourida Water Resources Journal*, no. August: 39–41.

Ministry of Environment. 2002. *Safe Drinking Water Act*. Drinking Water Legislation, Ministry of the Environment Ontario.

Mirchi, Ali, Kaveh Madani, David Watkins, and Sajjad Ahmad. 2012. "Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems." *Water Resources Management* 26 (9): 2421–42. doi:10.1007/s11269-012-0024-2.

Mohammadifardi, Hamed, Mark A. Knight, and Andre J.A. Unger. 2017. "Life Cycle Sustainability Assessment of Water and Wastewater Infrastructure Systems." In *Leadership in Sustainable Infrastructure*. Vancouver, BC: Canadian Society for Civil Engineering CSCE / SCGC.

Murray, A., I. Ray, and K. L. Nelson. 2009. "An Innovative Sustainability Assessment for Urban Wastewater Infrastructure and Its Application in Chengdu, China." *Journal of Environmental Management* 90 (11). Elsevier Ltd: 3553–60. doi:10.1016/j.jenvman.2009.06.009.

Ontario. 2017. *Ontario Regulation 588/17: Asset Management Planning for Municipal Infrastructure*.

Ontario Ministry of Infrastructure. 2017a. “Proposed Municipal Asset Management Planning Regulation.” *Environment Registry 013-0551*. https://www.ebr.gov.on.ca/ERS-WEB-External/displaynoticecontent.do?noticeId=MTMyNTkw&statusId=MjAxMzgx.

———. 2017b. “Update on Municipal Asset Management Planning.” In *Municipal Finance Officers’ Association Conference*. Municipal finance officers’ association.

Parkinson, J, M Schütze, and D Butler. 2005. “Modelling the Impacts of Domestic Water Conservation on the Sustain Ability of the Urban Sewerage System.” *Water and Environment Journal* 19 (1): 49–56. doi:10.1111/j.1747-6593.2005.tb00548.x.

Prosser, Monica, Vanessa Speight, and Yves Filion. 2013. “Life-Cycle Energy Analysis of Performance- Versus Age-Based Pipe Replacement Schedules.” *Journal - American Water Works Association* 105: E721–32. doi:10.5942/jawwa.2013.105.0157.

Racoviceanu, Alina I., Bryan W. Karney, Christopher a. Kennedy, and Andrew F. Colombo. 2007. “Life-Cycle Energy Use and Greenhouse Gas Emissions Inventory for Water Treatment Systems.” *Journal of Infrastructure Systems* 13 (4): 261–70. doi:10.1061/(ASCE)1076-0342(2007)13:4(261).

Rehan, Rashid. 2011. “Sustainable Municipal Water and Wastewater Management Using System Dynamics.”

Rehan, Rashid, and Mark Knight. 2007. “Do Trenchless Pipeline Construction Methods Reduce Greenhouse Gas Emissions?”

Rehan, Rashid, Mark A. Knight, Carl T. Haas, and Andreh J. A. Unger. 2011. “Application of System Dynamics for Developing Financially Self-Sustaining Management Policies for Water and Wastewater Systems.” *Water Research* 45 (16). Elsevier Ltd: 4737–50. doi:10.1016/j.watres.2011.06.001.

Rehan, Rashid, Mark A. Knight, Andreh J. A. Unger, and Carl T. Haas. 2014. “Financially Sustainable Management Strategies for Urban Wastewater Collection Infrastructure - Development of a System Dynamics Model.” *Tunnelling and Underground Space*

Technology 39. Elsevier Ltd: 116–29. doi:10.1016/j.tust.2012.12.003.

Rehan, Rashid, Mark A. Knight, Andreh J A Unger, and Carl T. Haas. 2013. “Development of a System Dynamics Model for Financially Sustainable Management of Municipal Watermain Networks.” *Water Research* 47 (20). Elsevier Ltd: 7184–7205. doi:10.1016/j.watres.2013.09.061.

Rehan, Rashid, Andre A.J. Unger, Mark A. Knight, and Carl T. Haas. 2015a. “Strategic Water Utility Management and Financial Planning Using a New System Dynamics Tool.” *Journal - American Water Works Association* 107 (1): E22–36. doi:10.5942/jawwa.2015.107.0006.

Rehan, Rashid, Andre J.A. Unger, Mark A. Knight, and Carl T. Haas. 2015b. “Strategic Water Utility Management and Financial Planning Using a New System Dynamics Tool.” *Journal American Water Works Association* 107 (1): 22–36.

Richmond, Barry. 1997. *An Introduction to Systems Thinking*.

Sahely, Halla R, Christopher a Kennedy, and Barry J Adams. 2005. “Developing Sustainability Criteria for Urban Infrastructure Systems.” *Canadian Journal of Civil Engineering* 32 (1): 72–85. doi:10.1139/l04-072.

Sahely, Halla R, Heather L MacLean, Hugh D Monteith, and David M Bagley. 2006. “Comparison of On-Site and Upstream Greenhouse Gas Emissions from Canadian Municipal Wastewater Treatment Facilities.” *Journal of Environmental Engineering and Science* 5 (5): 405–15. doi:10.1139/s06-009.

Sala, Serenella, Biagio Ciuffo, and Peter Nijkamp. 2013. “A Meta-Framework for Sustainability Assessment Research Memorandum 2013-16 Serenella Sala Biagio Ciuffo Peter Nijkamp A Meta - Framework for Sustainability Assessment.”

Sawah, Sondoss El, Alan McLucas, and Mike Ryan. 2010. “Using Cognitive Mapping to Elicit Modelling Requirements: An Overview.” *Proceedings of the 2010 18th IEEE International Requirements Engineering Conference, RE2010*, 357–63. doi:10.1109/RE.2010.51.

Sharma, Ashok K., Andrew L. Grant, Tim Grant, Francis Pamminger, and Lisa Opray. 2009. "Environmental and Economic Assessment of Urban Water Services for a Greenfield Development." *Environmental Engineering Science* 26 (5): 921–34. doi:10.1089/ees.2008.0063.

Singh, Rajesh Kumar, H.R. Murty, S.K. Gupta, and A.K. Dikshit. 2012. "An Overview of Sustainability Assessment Methodologies." *Ecological Indicators* 15 (1): 281–99. doi:10.1016/j.ecolind.2011.01.007.

Statistics Canada. 2018. "Non-Residential Building Construction Price Index, Fourth Quarter 2016." Accessed October 31. https://www150.statcan.gc.ca/n1/daily-quotidien/170214/dq170214a-eng.htm.

Sterman, John. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill.

Tsagarakis, K. P., D. D. Mara, and A. N. Angelakis. 2003. "Application of Cost Criteria for Selection of Municipal Wastewater Treatment Systems." *Water, Air, and Soil Pollution* 142 (1–4): 187–210. doi:10.1023/A:1022032232487.

U.S. Environmental Protection Agenecy. 1980. "Construction Costs for Municipal Wastewater Treatment Plants." Washington D.C.

UN. 1992. "Agenda 21 - Earth Summit."

United State Environmental Protection Agency (US EPA). 2018. "Understanding Global Warming Potentials." Accessed October 6. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

Upadhyaya, Jyoti Kumari. 2013. "A Sustainability Assessment Framework for Infrastructure : Application in Stormwater Systems."

US Environmental Protection Agency (EPA). 2014. "Guide for Estimating Infiltration and Inflow, June 2014," 1–7.

WOWCA. 2017. “Water Opportunities and Water Conservation Act, 2010, S.O. 2010, c. 19 - Bill 72 | Ontario.Ca.” Accessed January 5. http://www.ontario.ca/laws/statute/s10019.

WRc. 2011. *Sewerage Rehabilitation Manual*. Swindon, U.K.: Water Research Centre.

Xue, Xiaobo, Mary E Schoen, Xin Cissy Ma, Troy R Hawkins, Nicholas J Ashbolt, Jennifer Cashdollar, and Jay Garland. 2015. “Critical Insights for a Sustainability Framework to Address Integrated Community Water Services: Technical Metrics and Approaches.” *Water Research* 77. Elsevier Ltd: 155–69. doi:10.1016/j.watres.2015.03.017.

Younis, Rizwan. 2011. “Development of Wastewater Collection Network Asset Database, Deterioration Models and Management Framework.” University of Waterloo, Canada.

Appendix A

Demonstration system dynamics model for management of wastewater collection and treatment plant systems

A 1 Wastewater collection and treatment physical sector

A 1.1 ICG_1

Type	Stock
Unit	Kilometer
Equation	$ICG\_1(t) = ICG\_1(t - dt) + (SwPipes5\_Rehab + New\_Pipe\_Installation + SwPipes4\_Rehab - SwPipes\_Deterioration\_1\_to\_2) * dt$
Description	Length of pipes in the first (best) condition grade
Initial Value	140
Reference for definition of independent variables	
$SwPipes5\_Rehab$	Object A1.2
$New\_Pipe\_Instalation$	Object A1.4
$SwPipes4\_Rehab$	Object A1.8
$SwPipes\_Deterioration\_1\_to\_2$	Object A1.5

A 1.2 $SWPipes5\_Rehab$

Type	Flow
Unit	Kilometer per year
Equation	$SwPipes5\_Rehab = SwPipes5\_Rehab\_Rate$
Description	Represents the annual replacement of sewer pipes in worst condition and moving pipes from stock ICG_5 to stock ICG_1.
Initial Value	Not applicable
Reference for definition of independent variables	
$SwPipes5\_Rehab\_Rate$	Object A1.3

A 1.3 $SwPipes5\_Rehab\_Rate$

Type	Convertor (constant)
Unit	Kilometer per year
Equation	Not applicable (defined by the user)
Description	It is the total length of the ICG_5 pipes that is to be replaced every year. Its value is specified by the model user for any simulation scenario and it then remains constant throughout the simulation
Initial Value	Depending upon the user input it can vary from 0 to any positive number.

A 1.4 $New\_Pipe\_Installation$

Type	Flow
Unit	Kilometer per year
Equation	$New\_Pipe\_Installation\ =\ (100 - Urban\_Densification)/100\ *$ $(Population\_\_Growth\_rate/100 * Total\_Network\_Length)$
Description	Represents the annual length of new sewer pipes installed to extend the sewer network for new developed urban area. The new pipes have the best condition and are added to the stock ICG_1.
Initial Value	Not applicable
Reference for definition of independent variables	
$Urban\_Densification$	Object A1.5
$Population\_\_Growth\_rate$	Object A2.4
$Total\_Network\_Length$	Object A1.7

A 1.5 $SwPipes\_Deterioration\_1\_to\_2$

Type	Flow
Unit	Kilometer per year
Equation	$SwPipes\_Deterioration\_1\_to\_2\ =\ ICG\_1/43$
Description	Represents the deterioration process of the pipes. Moves pipe lengths from stock ICG_1 to ICG_2.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_1	Object A1.1

A 1.6 $Urban\_Densification$

Type	Convertor (constant)
Unit	Percentage
Equation	Not applicable (defined by the user)
Description	It can be adjusted from 0 to 100 percent by the model users to define the fraction of new population that will reside in the current urban area. A 0% urban densification represents the sewer network length expands at the same rate as the population growth rate.
Initial Value	Depending upon the user input it can vary from 0 to any positive number.

A 1.7 $Total\_Network\_length$

Type	Convertor
Unit	Kilometer
Equation	$Total\_Network\_Length = ICG\_1 + ICG\_2 + ICG\_3 + ICG\_4 + ICG\_5$
Description	It adds up the total length of pipes in all condition group stocks. Thus it represents the total length of the pipe network.
Initial Value	700
Reference for definition of independent variables	
ICG_1	Object A1.
ICG_2	Object A1.
ICG_3	Object A1.
ICG_4	Object A1.

A 1.8 $SWPipes4\_Rehab$

Type	Flow
Unit	Kilometer per year
Equation	$SwPipes4\_Rehab = SwPipes4\_Rehab\_Rate$
Description	Represents the annual rehabilitation of ICG_4 sewer pipes and moving pipes from stock ICG_4 to stock ICG_1.
Initial Value	Not applicable
Reference for definition of independent variables	
$SwPipes5\_Rehab\_Rate$	Object A1.9

A 1.9 $SwPipes4\_Rehab\_Rate$

Type	Convertor
Unit	Kilometer per year
Equation	Not applicable (defined by the user)
Description	It is the total length of the ICG_4 pipes that is to be rehabilitated by or relined by trenchless technologies every year. Its value is specified by the model user for any simulation scenario and it then remains constant throughout the simulation
Initial Value	Depending upon the user input it can vary from 0 to any positive number.

A 1.10 ICG_2

Type	Stock
Unit	Kilometer
Equation	$ICG\_2(t) = ICG\_2(t - dt) + (SwPipes\_Deterioration\_1\_to\_2 - SwPipes\_Deterioration\_2\_to\_3) * dt$
Description	Length of pipes in the second condition grade
Initial Value	280
Reference for definition of independent variables	
$SwPipes\_Deterioration\_1\_to\_2$	Object A1.5
$SwPipes\_Deterioration\_2\_to\_3$	Object A1.11

A 1.11 $SwPipes\_Deterioration\_2\_to\_3$

Type	Flow
Unit	Kilometer per year
Equation	$SwPipes\_Deterioration\_2\_to\_3 = ICG\_2/25$
Description	Represents the deterioration process of the pipes. Moves pipe lengths from stock ICG_2 to ICG_3.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_2	Object A1.11

A 1.12 ICG_3

Type	Stock
Unit	Kilometer
Equation	$ICG\_3(t) = ICG\_3(t - dt) + (SwPipes\_Deterioration\_2\_to\_3 - SwPipes\_Deterioration\_3\_to\_4) * dt$
Description	Length of pipes in the third condition grade
Initial Value	140
Reference for definition of independent variables	
$SwPipes\_Deterioration\_2\_to\_3$	Object A1.11
$SwPipes\_Deterioration\_3\_to\_4$	Object A1.13

A 1.13 $SwPipes\_Deterioration\_3\_to\_4$

Type	Flow
Unit	Kilometer per year
Equation	$SwPipes\_Deterioration\_3\_to\_4 = ICG\_3/18$
Description	Represents the deterioration process of the pipes. Moves pipe lengths from stock ICG_3 to ICG_4.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_3	Object A1.12

A 1.14 ICG_4

Type	Stock
Unit	Kilometer
Equation	$ICG\_4(t) = ICG\_4(t - dt) + (SwPipes\_Deterioration\_3\_to\_4 - SwPipes\_Deterioration\_4\_to\_5 - SwPipes4\_Rehab) * dt$
Description	Length of pipes in the fourth condition grade
Initial Value	105
Reference for definition of independent variables	
$SwPipes\_Deterioration\_3\_to\_4$	Object A1.13
$SwPipes\_Deterioration\_4\_to\_5$	Object A1.15
$SwPipes4\_Rehab$	Object A1.8

A 1.15 $SwPipes\_Deterioration\_4\_to\_5$

Type	Flow
Unit	Kilometer per year
Equation	$SwPipes\_Deterioration\_4\_to\_5 = ICG\_2/14$
Description	Represents the deterioration process of the pipes. Moves pipe lengths from stock ICG_4 to ICG_5.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_4	Object A1.14

A 1.16 ICG_5

Type	Stock
Unit	Kilometer
Equation	$ICG\_5(t) = ICG\_5(t - dt) + (SwPipes\_Deterioration\_4\_to\_5 - SwPipes5\_Rehab) * dt$
Description	Length of pipes in the fifth condition grade
Initial Value	34
Reference for definition of independent variables	
$SwPipes\_Deterioration\_4\_to\_5$	Object A1.17
$SwPipes5\_Rehab$	Object A1.2

A 1.17 $I\&I\_Rate\_by\_Grade[1]$

Type	Convertor (constant)
Unit	Cubic meter per kilometer per day
Equation	Not applicable
Description	It represents the unit inflow and infiltration rate to pipes in the first (best) condition grade (ICG1).
Initial Value	0

A 1.18 $I\&I\_Rate\_by\_Grade[2]$

Type	Convertor (constant)
Unit	Cubic meter per kilometer per day
Equation	Not applicable
Description	It represents the unit inflow and infiltration rate to pipes in the second condition grade (ICG2).
Initial Value	0

A 1.19 $I\&I\_Rate\_by\_Grade[3]$

Type	Convertor (constant)
Unit	Cubic meter per kilometer per day
Equation	Not applicable
Description	It represents the unit inflow and infiltration rate to pipes in the third condition grade (ICG3).
Initial Value	4.8

A 1.20 $\boldsymbol{I\&I\_Rate\_by\_Grade}[\mathbf{4}]$

Type	Convertor (constant)
Unit	Cubic meter per kilometer per day
Equation	Not applicable
Description	It represents the unit inflow and infiltration rate to pipes in the fourth condition grade (ICG4).
Initial Value	12

A 1.21 $\boldsymbol{I\&I\_Rate\_by\_Grade}[\mathbf{5}]$

Type	Convertor (constant)
Unit	Cubic meter per kilometer per day
Equation	Not applicable
Description	It represents the unit inflow and infiltration rate to pipes in the fifth (worst) condition grade (ICG5).
Initial Value	91.2

A 1.22 $\boldsymbol{Pipes\_Lengths}[\mathbf{1}]$

Type	Convertor
Unit	kilometer
Equation	$Pipes\_Lengths[1] = ICG\_1$
Description	It represents the total length of pipes in the first (best) condition grade stcok.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_1	Object A1.1

A 1.23 $\boldsymbol{Pipes\_Lengths}[\mathbf{2}]$

Type	Convertor
Unit	kilometer
Equation	$Pipes\_Lengths[2] = ICG\_2$
Description	It represents the total length of pipes in the second condition grade stock.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_2	Object A1.10

A 1.24 $\boldsymbol{Pipes\_Lengths}[\mathbf{3}]$

Type	Convertor
Unit	kilometer
Equation	$Pipes\_Lengths[3] = ICG\_3$
Description	It represents the total length of pipes in the third condition grade stock.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_3	Object A1.12

A 1.25 $\boldsymbol{Pipes\_Lengths[4]}$

Type	Convertor
Unit	kilometer
Equation	$Pipes\_Lengths[5] = ICG\_4$
Description	It represents the total length of pipes in the fourth condition grade stock.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_4	Object A1.14

A 1.26 $\boldsymbol{Pipes\_Lengths[5]}$

Type	Convertor
Unit	kilometer
Equation	$Pipes\_Lengths[5] = ICG\_5$
Description	It represents the total length of pipes in the fifth condition grade stock.
Initial Value	Not applicable
Reference for definition of independent variables	
ICG_5	Object A1.15

A 1.27 $\boldsymbol{Annual\_I\&I\_\_Flow}$

Type	Convertor
Unit	Cubic meter per year
Equation	$Annual\_I\&I\_\_Flow = Convert\_Year\_to\_Day * (I\&I\_Rate\_by\_Grade[1] * Pipes\_Lengths[1] + I\&I\_Rate\_by\_Grade[2] * Pipes\_Lengths[2] + I\&I\_Rate\_by\_Grade[3] * Pipes\_Lengths[3] + I\&I\_Rate\_by\_Grade[4] * Pipes\_Lengths[4] + I\&I\_Rate\_by\_Grade[5] * Pipes\_Lengths[5])$
Description	It represents the total annual inflow and infiltration to the sewer network.
Initial Value	Not applicable
Reference for definition of independent variables	
$Convert\_Year\_to\_Day$	Object A1.28
$Pipes\_Lengths[1]$	Object A1.22
$I\&I\_Rate\_by\_Grade[1]$	Object A1.17
$Pipes\_Lengths[2]$	Object A1.23
$I\&I\_Rate\_by\_Grade[2]$	Object A1.18
$Pipes\_Lengths[3]$	Object A1.24
$I\&I\_Rate\_by\_Grade[3]$	Object A1.19
$Pipes\_Lengths[4]$	Object A1.25
$I\&I\_Rate\_by\_Grade[4]$	Object A1.20
$Pipes\_Lengths[5]$	Object A1.26
$I\&I\_Rate\_by\_Grade[5]$	Object A1.21

A 1.28 $Convert\_year\_to\_Day$]

Type	Convertor (constant)
Unit	Day/year
Equation	Not applicable
Description	It is used to convert the values in unit day to values in unit year
Initial Value	365

A 1.29 $AnnualTotal\_Sewage\_Flow$

Type	Convertor
Unit	Cubic meter per year
Equation	$AnnualTotal\_Sewage\_Flow = Annual\_I\&I\_\_Flow + Sanitary\_Sewage\_Flow$
Description	It represents the total annual wastewater flow to the wastewater treatment plant.
Initial Value	Not applicable
Reference for definition of independent variables	
$Annual\_I\&I\_\_Flow$	Object A1.27
$Sanitary\_Sewage\_Flow$	Object A2.11

A 1.30 $WWTP\_Capacity$

Type	Stock
Unit	Cubic meter per day
Equation	$WWTP\_Capacity(t) = WWTP\_Capacity(t - dt) + (New\_Capacity\_Construction) * dt$
Description	Total wastewater treatment plant capacity
Initial Value	40,000
Reference for definition of independent variables	
$New\_Capacity\_Construction$	Object A1.31

A 1.31 $New\_Capacity\_Construction$

Type	Flow
Unit	Cubic meter per day per year
Equation	$New\_Capacity\_Construction = MAX((AnnualTotal\_Sewage\_Flow/Convert\_Year\_to\_Day) * (1 + (Required\_\_Reserve\_Capacity/100)) - WWTP\_Capacity, 0)$
Description	It calculate the WWTP capacity building requirement for treating the additional volume of wastewater in each year.
Initial Value	Not applicable
Reference for definition of independent variables	
$AnnualTotal\_Sewage\_Flow$	Object A1.29
$Convert\_Year\_to\_Day$	Object A1.28
$Required\_\_Reserve\_Capacity$	Object A1.32
$WWTP\_Capacity$	Object A1.30

A 1.32 $\boldsymbol{Required\_Reserve\ \_Capacity}$]

Type	Convertor (constant)
Unit	Percentage
Equation	Not applicable
Description	It represents the initial percentage of the WWTP capacity which is considered as reserved capacity and to be maintained in future.
Initial Value	25

A 2 Consumer Sector

A 2.1 $Water\_Demand$

Type	Stock
Unit	Liter per capita per day
Equation	$Water\_Demand(t) = Water\_Demand(t - dt) + (- Price\_Induced\_Reduction) * dt$
Description	It is the average water consumed by a person in a day
Initial Value	300
Reference for definition of independent variables	
$Price\_Induced\_Reduction$	Object A2.1

A 2.2 $Price\_Induced\_Reduction$

Type	Flow
Unit	Liters per capita per day per year
Equation	$Price\_Induced\_Reduction = MIN((User\_Fees - delay(User\_Fees, 1))/(delay(User\_Fees, 1)) * Price\_Elasticity * Water\_Demand, (Water\_Demand - Minimum\_Water\_Demand))$
Description	It is the change in water demand caused by an increase in $User\_Fees$. It makes use of $DELAY$ () function. The function $DELAY(user\ Fees, 1)$, returns a value of $User\_Fee$ delayed by 1 year i.e. the value of previous year's $User\_Fees$. Furthermore, the equation makes use of the $MIN()$ function, which returns the lesser of the value for the two expressions enclosed inside this function. This formulation is employed to ensure that the $Demand\_Change$ will not cause the value of $Water\_Demand$ to fall below its lower limit specified as Min_Water_Demand. Finally, it should be noted that the flow $Demand\_Change$ is a unidirectional outflow for stock $Water\_Demand$. This means that $Demand\_Change$ can only assume non-negative values.
Initial Value	Not applicable
Reference for definition of independent variables	
$User\_Fees$	Object A3.1
$Price\_Elasticity$	Object A2.3
$Water\_Demand$	Object A2.1
$Minimum\_Water\_demand$	Object A2.4

A 2.3 $Price\_Elasticity$

Type	Convertor (constant)
Unit	Percent/percent (dimensionless)
Equation	Not applicable
Description	It is equal to the percentage change in $Water\_Demand$ divided by the percentage change in $User\_Fee$. Its value is specified by user for any simulation scenario and it then remains constant throughout the simulation. It is customary to omit the negative sign from price elasticity value. The same has been used in this model, e.g., if users wish to specify a -0.35 value for the $Price\_Elasticity$, then they simply need to input it as 0.35.
Initial Value	Depending upon the user input it can vary from 0 to 1. However, all simulation scenarios reported in this study use a value of either 0 or 0.35

A 2.4 $Minimum\_Water\_Demand$

Type	Convertor (constant)
Unit	Liters per capita per day
Equation	Not applicable
Description	It is the lower limit imposed on $Water\_Demand$. Hence, the value of $Water\_demand$ cannot decrease beyond $Minimum\_Demand$ regardless of the increase in $User\_Fee$. Its value is specified by the user for any simulation scenario and it then remains constant throughout the simulation.
Initial Value	200

A 2.5 $Population\_growth\_rate$

Type	Convertor (constant)
Unit	Percentage
Equation	Not applicable
Description	It represents the growth rate of the population and varies between 0 to 100 percent.
Initial Value	0.1

A 2.6 $Population$

Type	Stock
Unit	Person
Equation	$Population(t) = Population(t - dt) + (Population\_increase) * dt$
Description	It is the total number of people served by the utility.
Initial Value	100,000
Reference for definition of independent variables	
$Population\_increase$	Object A2.7

A 2.7 $Population\_Increase$

Type	Flow
Unit	Not applicable
Equation	$Population\_increase = (Population * Population\_\_Growth\_rate/100)$
Description	It is the total number of people served by the utility.
Initial Value	100,000
Reference for definition of independent variables	
$Population\_Growth\_rate$	Object A2.4
$Population$	Object A2.6

A 2.8 $Annual\_Water\_Consumption$

Type	Convertor
Unit	Not applicable
Equation	$Annual\_Water\_Consumption = SMTH3(Water\_Demand, Demand\_Adjustment\_Period) * Population * Convert\_Year\_to\_Day/Covnert\_M3\_to\_L$
Description	It is the annual volume of water consumed by utility customers. It makes use of $SMTH3$ () function. Instead of immediately implementing a new value of $Water\_Demand$, $SMTH$ (3) function implements the new value over the $Water\_Deamnd\_Adjustment\_period$. For further discussion refer to Section 4.2 and Figure 4 in Rehan (2011).
Initial Value	Not applicable
Reference for definition of independent variables	
$Water\_Demand$	Object A2.1
$Adjustment\_Period$	Object A2.9
$Population$	Object A2.6
$Convert\_Year\_to\_Day$	Object A1.28
$Covnert\_M3\_to\_L$	Object A2.10

A 2.9 $Deamand\_Adjustment\_Period$

Type	Convertor (constant)
Unit	Year
Equation	Not applicable
Description	It is the time period over which a change in $Water\_Demand$ is implemented.
Initial Value	Depending upon the user input it can vary from 1 to 100 years. A value of 20 years is used in this study.

A 2.10 $Convert\_M3\_to\_L]$

Type	Convertor (constant)
Unit	l/m^3
Equation	Not applicable
Description	It is used to convert the values in cubic meter unit to liter.
Initial Value	1,000

A 2.11 $Sanitory\_Sewage\_Flow$

Type	Convertor
Unit	M^3 per year
Equation	$Sanitary\_Sewage\_Flow\ =\ Annual\_Water\_Consumption * (100 - Consumptive\_Use\_Fraction) * 0.01$
Description	It is the annual volume of sewage generated by consumers
Initial Value	Not applicable
Reference for definition of independent variables	
$Annual\_Water\_Consumption$	Object A2.8
$Consumptive\_Use\_Fraction$	Object A2.12

A 2.12 $Consumptive\_Use\_Fraciton$

Type	Convertor
Unit	Percentage (dimensionless)
Equation	Not applicable
Description	It is the fraction of the $Water\_Demand$ consumed by an average consumer and is not discharged to the sewer system.
Initial Value	10

A 2.13 $Average\_annual\_houshold\_Income$

Type	Convertor (constant)
Unit	\$/year
Equation	Not applicable
Description	It is the average annual household income.
Initial Value	60,000

A 2.14 $Average\_Family\_size$

Type	Convertor (constant)
Unit	Person
Equation	Not applicable
Description	It is the average number of people in a household.
Initial Value	2.5

A 2.15 $Annual\_Service\_Fee$

Type	Convertor
Unit	\$/year
Equation	$Annual\_\_service\_Fee = Avg\_Family\_size * (Water\_Demand / Covnert\_M3\_to\_L * Convert\_Year\_to\_Day) * User\_Fees$
Description	It represents the bill burden as the percent share of the wastewater collection and treatment bill from the household income.
Initial Value	Not applicable
Reference for definition of independent variables	
$Water\_Demand$	Object A2.1
$Covnert\_M3\_to\_L$	Object A2.10
$Convert\_Year\_to\_Day$	Object A1.28
$User\_Fees$	Object A3.5

A 2.16 $Affordability$

Type	Convertor
Unit	Percent (dimensionless)
Equation	$Affordability = (Annual\_\_service\_Fee / Average\_Annual\_Household\_Income) * 100$
Description	It represents the bill-burden as the percent share of the annual wastewater collection and treatment total bill from the annual household income.
Initial Value	Not applicable
Reference for definition of independent variables	
$Annual\_\_service\_Fee$	Object A2.15
$verage\_Annual\_Household\_Income$	Object A2.13

A 3 Wastewater collection and treatment finance sector

A 3.1 $User\_Fee$

Type	Stock
Unit	Dollar per cubic meter
Equation	$User\_Fees(t) = User\_Fees(t - dt) + (User\_Fee\_Hike - User\_Fee\_Decline) * dt$
Description	It is the amount (dollars) that the utility charges its customers for every cubic meter of water consumed. In this study, $User\_Fee$ is assumed to cover the charges for both wastewater collection and treatment services.
Initial Value	2.5
Reference for definition of independent variables	
$User\_Fee\_Hike$	Object A3.2
$User\_Fee\_Decline$	Object A3.3

A 3.2 $User\_Fee\_Hike$

Type	Flow
Unit	Dollar per cubic meter per year
Equation	$User\_Fee\_Hike = (MIN\ (Max\_Fee\_\_Hike\_Rate/100 * User\_Fees, ((Annual\_\_Expenditures - Funds\_\_Balance)/Annual\_Water\_Consumption - User\_Fees)))/DT$
Description	The MIN () function is used to limit the $User\_Fee$ increase in each year between the rate of increase required to pay the $Annual\_Expenditure$ and the allowed $Max\_Fee\_Hike\_Rate$ specified by the model user.
Initial Value	Not applicable
Reference for definition of independent variables	
$Max\_Fee\_\_Hike\_Rate$	Object A3.4
$User\_Fee$	Object A3.1
$Annual\_\_Expenditures$	Object A3.6
$Funds\_\_Balance$	Object A3.5
$Annual\_Water\_Consumption$	Object A2.8

A 3.3 $User\_Fee\_Decline$

Type	Flow
Unit	Dollar per cubic meter per year
Equation	$User\_Fee\_Decline\ =\ IF\ (Funds\_\_Balance > 0)\ THEN\ (User\_Fees - ((Annual\_\_Expenditures - Funds\_\_Balance)/ Annual\_Water\_Consumption))\ ELSE\ 0$
Description	The above equation first checks whether $Fund\_Balanc$ is greater than 0. If true, the $User\_Fee$ is decreased to the level that the surplus can be eliminated in the next year. If false, then it will be 0.
Initial Value	Not applicable
Reference for definition of independent variables	
$User\_Fee$	Object A3.1
$Annual\_\_Expenditures$	Object A3.6
$Funds\_\_Balance$	Object A3.5
$Annual\_Water\_Consumption$	Object A2.8

A 3.4 $Max\_Fee\_Hike\_Rate$

Type	Convertor (constant)
Unit	Percent per year
Equation	Not applicable (defined by the user)
Description	It represents the maximum percent increase of the $User\_Fee$ per annum and is defined by the model user. To achieve the financial sustainability, the $Max\_Fee\_Hike\_Rate$ should be high enough so that it can generate enough revenues to pay the wastewater collection and treatment annual operational and capital expenses. This value should be find by trial and error.
Initial Value	Depending upon the user input, it can vary from 0 to 100.

A 3.5 $Fund\_Balance$

Type	Stock
Unit	Dollar
Equation	$Funds\_\_Balance(t)\ =\ Funds\_\_Balance(t\ -\ dt)\ +\ (Revenue\ -\ OpEx\ -\ CapEx)\ *\ dt$
Description	Represents the utility fund balance.
Initial Value	0
Reference for definition of independent variables	
$Revenue$	Object A3.7
$CapEx$	Object A3.9
$OpEx$	Object A3.8

A 3.6 $\boldsymbol{Annual\_Expenditure}$

Type	Convertor
Unit	Dollar per year
Equation	$Annual\_\_Expenditures\ =\ OpEx + CapEx$
Description	It is the sum of annual operational and capital expenses of wastewater collection and treatment systems.
Initial Value	Not applicable
Reference for definition of independent variables	
$CapEx$	Object A3.9
$OpEx$	Object A3.8

A 3.7 $\boldsymbol{Revenue}$

Type	Flow
Unit	Dollar per cubic meter per year
Equation	$Revenue\ =\ User\_Fees * Annual\_Water\_Consumption$
Description	It is the utility income from user fee collection.
Initial Value	Not applicable
Reference for definition of independent variables	
$User\_Fee$	Object A3.1
$Annual\_Water\_Consumption$	Object A2.8

A 3.8 $\boldsymbol{Convert\_M3\_to\_L}]$

Type	Convertor (constant)
Unit	m/km
Equation	Not applicable
Description	It is used to convert kilometer unit to meter.
Initial Value	1000

A 3.9 $\boldsymbol{Unit\_price\_WWC\_\_OpEx[1]}$

Type	Convertor (constant)
Unit	Dollar/meter/year
Equation	Not applicable
Description	It represents the annual operation and maintenance cost of one meter pipe in the first (best) condition grade.
Initial Value	10

A 3.10 $\boldsymbol{Unit\_price\_WWC\_\_OpEx}[2]$

Type	Convertor (constant)
Unit	Dollar/meter/year
Equation	Not applicable
Description	It represents the annual operation and maintenance cost of one meter pipe in the second condition grade.
Initial Value	13

A 3.11 $\boldsymbol{Unit\_price\_WWC\_\_OpEx}[3]$

Type	Convertor (constant)
Unit	Dollar/meter/year
Equation	Not applicable
Description	It represents the annual operation and maintenance cost of one meter pipe in the third condition grade
Initial Value	16

A 3.12 $\boldsymbol{Unit\_price\_WWC\_\_OpEx}[4]$

Type	Convertor (constant)
Unit	Dollar/meter/year
Equation	Not applicable
Description	It represents the annual operation and maintenance cost of one meter pipe in the fourth condition grade.
Initial Value	120

A 3.13 $\boldsymbol{Unit\_price\_WWC\_\_OpEx}[5]$

Type	Convertor (constant)
Unit	Dollar/meter/year
Equation	Not applicable
Description	It represents the annual operation and maintenance cost of one meter pipe in the fifth (worst) condition grade.
Initial Value	24

A 3.14 $\boldsymbol{Unit\_price\_WWC\_\_CapEx}[\boldsymbol{New}]$

Type	Convertor (constant)
Unit	Dollar/kilometer
Equation	Not applicable
Description	It represents the capital cost of new pipe installation with open-cut trenching technologies.
Initial Value	1000,000

A 3.15 Unit_price_WWC__CapEx[Rehab51]

Type	Convertor (constant)
Unit	Dollar/kilometer
Equation	Not applicable
Description	It represents the capital cost of worst condition pipes’ replacement using open-cut trenching technologies.
Initial Value	1000,000

A 3.16 Unit_price_WWC__CapEx[Rehab 41]

Type	Convertor (constant)
Unit	Dollar/kilometer
Equation	Not applicable
Description	It represents the capital cost for relining pipes in fourth condition grade using trenchless technologies.
Initial Value	600,000

A 3.17 Unit_price_WWT__OpEx

Type	Convertor (constant)
Unit	Dollar/cubic meter
Equation	Not applicable
Description	It represents the annual operation and maintenance cost of WWTP normalized with total annual treated wastewater. In this study, the unit operational cost is assumed to be constant for the entire simulation period.
Initial Value	0.28

A 3.18 Unit_price_WWT__CapEx

Type	Convertor (constant)
Unit	Dollar/cubic meter
Equation	Not applicable
Description	It represents the cost of upgrading a wastewater treatment plant system for increasing its treatment capacity.
Initial Value	3,300

A 3.19 $OpEx$

Type	Flow
Unit	Dollar per cubic meter per year
Equation	$OpEx\ =\ (AnnualTotal\_Sewage\_Flow * Unit\_Price\_WWT\_\_OpEx) + (Convert\_Km\_to\_m\ * (Pipes\_Lengths[1] * Unit\_Price\_\_WWC\_OpEx[1] + Pipes\_Lengths[2] * Unit\_Price\_\_WWC\_OpEx[2] + Pipes\_Lengths[3] * Unit\_Price\_\_WWC\_OpEx[3] + Pipes\_Lengths[4] * Unit\_Price\_\_WWC\_OpEx[4] + Pipes\_Lengths[5] * Unit\_Price\_\_WWC\_OpEx[5])$
Description	It is the utility income from user fee collection.
Initial Value	Not applicable
Reference for definition of independent variables	
$AnnualTotal\_Sewage\_Flow$	Object A1.29
$Unit\_Price\_WWT\_\_OpEx$	Object A3.17
$Annual\_Water\_Consumption$	Object A2.8
$Convert\_Km\_to\_m$	Object A3.8
$Pipes\_Lengths[1]$	Object A1.22
$Unit\_Price\_\_WWC\_OpEx[1]$	Object A3.9
$Pipes\_Lengths[2]$	Object A1.23
$Unit\_Price\_\_WWC\_OpEx[2]$	Object A3.10
$Pipes\_Lengths[3]$	Object A1.24
$Unit\_Price\_\_WWC\_OpEx[3]$	Object A3.11
$Pipes\_Lengths[4]$	Object A1.25
$Unit\_Price\_\_WWC\_OpEx[4]$	Object A3.12
$Pipes\_Lengths[5]$	Object A1.26
$Unit\_Price\_\_WWC\_OpEx[5]$	Object A3.13

A 3.20 $CapEx$

Type	Flow
Unit	Dollar per cubic meter per year
Equation	$CapEx = New\_Capacity\_Construction * Unit\_Price\_WWT\_CapEx + (Unit\_price\_WWC\_CapEx[New] * New\_Pipe\_Installation + Unit\_price\_WWC\_CapEx[Rehab41] * SwPipes4\_Rehab + Unit\_price\_WWC\_CapEx[Rehab51] * SwPipes5\_Rehab)$
Description	It is the utility income from user fee collection.
Initial Value	Not applicable
Reference for definition of independent variables	
$New\_Capacity\_Construction$	Object A1.31
$Unit\_Price\_WWT\_\_CapEx$	Object A3.18
$Unit\_price\_WWC\_CapEx[New]$	Object A3.14
$New\_Pipe\_Installation$	Object A1.4
$Unit\_price\_WWC\_CapEx[Rehab41]$	Object A3.15
$SwPipes4\_Rehab$	Object A1.9
$Unit\_price\_WWC\_CapEx[Rehab51]$	Object A3.16
$SwPipes5\_Reha$	Object A1.3

A 4 Environmental Sector

A 4.1 GHG_EF_ICG5_OpenCut_Trenching

Type	Convertor (constant)
Unit	kg CO2/meter pipe
Equation	Not applicable
Description	It represents the GHG emissions from construction activities for replacement of ICG5 pipes or extending the sewer network. It also includes the emission resulted from traffic disruptions.
Initial Value	64

A 4.2 GHG_EF_ICG5_Trenchless

Type	Convertor (constant)
Unit	kg CO2/meter pipe
Equation	Not applicable
Description	It represents the GHG emissions from construction activities for rehabilitation and relining of ICG4using trenchless technologies. It also includes the emission resulted from traffic disruptions.
Initial Value	2

A 4.3 N2O_Annual_Emission_rate_per_capita

Type	Convertor (constant)
Unit	kg CO2/person/year
Equation	Not applicable
Description	It is the average N2O emission at the wastewater collection systems and treatment plants in Canada based on the Intergovernmental panel on climate change (IPCC) recommendation.
Initial Value	0.004

A 4.4 N2O_GWP_factor

Type	Convertor (constant)
Unit	Kg CO2/Kg N2O
Equation	Not applicable
Description	It represents the relative potency of one kg N2O gas emission in global warming compared with one kg of CO2 gas emission over 100 years.
Initial Value	296

A 4.5 CH4_Annual_Emission_rate_per_capita

Type	Convertor (constant)
Unit	kg CO2/person/year
Equation	Not applicable
Description	It is the average CH4 emission at the wastewater collection system and treatment plants in Canada based on the Intergovernmental panel on climate change (IPCC) recommendation.
Initial Value	0.0

A 4.6 CH4_GWP_factor

Type	Convertor (constant)
Unit	Kg CO2/Kg CH4
Equation	Not applicable
Description	It represents the relative potency of one kg CH4 gas emission in global warming compared with one kg of CO2 gas emission over 100 years.
Initial Value	28

A 4.7 Energy_use_rate_for_sewage_treatment

Type	Convertor (constant)
Unit	Mega joule per cubic meter
Equation	Not applicable
Description	It is the average electric-energy use rate for treating wastewaters at the WWTPs of studied city.
Initial Value	1.53009

A 4.8 Energy_use_rate_for_sewage_pump

Type	Convertor (constant)
Unit	Mega joule per cubic meter
Equation	Not applicable
Description	It is the average electric-energy use rate for pumping wastewater at the sewer network system of studied city.
Initial Value	0.230201

A 4.9 Energy_use_rate_for_water_distributio

Type	Convertor (constant)
Unit	Mega joule per cubic meter
Equation	Not applicable
Description	It is the average electric-energy use rate for pumping water from the water treatment plants to water users for the studied system.
Initial Value	1.2243

A 4.10 GHG_EF_Ontario_electricity

Type	Convertor (constant)
Unit	Kg CO2/kwh
Equation	Not applicable
Description	It is the average CO2 emissions for the electricity generation from various energy resources in Ontario. The value is taken from: http://www.nrcan.gc.ca/energy/efficiency/industry/technical-info/benchmarking/canadian-steel-industry/5193
Initial Value	0.87

A 4.11 Energy_use_rate_for_water_treatment

Type	Convertor (constant)
Unit	Mega joule per cubic meter
Equation	Not applicable
Description	It is the average electric-energy use rate for pumping water from the water treatment plants to water users for the studied system.
Initial Value	2.4

A 4.12 Convert_MJ_KWh

Type	Convertor (constant)
Unit	Kwh/mega joule
Equation	Not applicable
Description	It convert the values in mega joule to kwh unit
Initial Value	0.277778

A 4.13 Annual_GHG_emission_from_replacement&new_pipe_instalation

Type	Convertor
Unit	Kg CO2 per year
Equation	$Annual\_GHG\_emission\_from\_replacement\&new\_pipe\_instalation = GHG\_EF\_ICG5\_\_OpenCut\_Trenching * (New\_Pipe\_Installation + SwPipes5\_Rehab) * Convert\_Km\_to\_m)$
Description	It is the total annual GHG emission from capital work activities for replacement of ICG5 or installation of new pipes at the WWC system.
Initial Value	Not applicable
Reference for definition of independent variables	
$GHG\_EF\_ICG5\_\_OpenCut\_Trenching$	Object A4.1
$New\_Pipe\_Installation$	Object A1.4
$SwPipes5\_Rehab$	Object A1.2
$Convert\_Km\_to\_m$	Object A3.8

A 4.14 $Annual\_GHG\_emission\_from\_rehabilitation$

Type	Convertor
Unit	Kg CO2 per year
Equation	$Annual\_GHG\_Emission\_from\_\_rehabilitation = GHG\_EF\_ICG4\_Trenchless * SwPipes4\_Rehab * Convert\_Km\_to\_m$
Description	It is the total annual GHG emission from capital work activities for rehabilitation of ICG4 pipes at the WWC system.
Initial Value	Not applicable
Reference for definition of independent variables	
$GHG\_EF\_ICG4\_Trenchless$	Object A4.2
$SwPipes4\_Rehab$	Object A1.9
$Convert\_Km\_to\_m$	Object A3.8

A 4.15 $Annual\_GHG\_emission\_for\_sewage\_treatment\_process$

Type	Convertor
Unit	Kg CO2 per year
Equation	$Annual\_GHG\_Emission\_\_for\_sewage\_treatment\_\_processes = Population * ((N2O\_Annual\_Emission\_rate\_per\_capita * N2O\_\_GWP\_factor) + (CH4\_Annual\_\_Emission\_rate\_per\_capita * CH4\_GWP\_factor))$
Description	It is the total annual GHG emission from wastewater treatment plants.
Initial Value	Not applicable
Reference for definition of independent variables	
$N2O\_Annual\_Emission\_rate\_per\_capita$	Object A4.3
$N2O\_\_GWP\_factor$	Object A4.4
$CH4\_Annual\_\_Emission\_rate\_per\_capita$	Object A4.5
$CH4\_GWP\_factor$	Object A4.6
$Population$	Object A2.6

A 4.16 $Annual\_Energy\_used\_for\_water\_treatment$

Type	Flow
Unit	Mega joule per year
Equation	$Annual\_\_energy\_used\_for\_water\_treatment = (Annual\_Water\_Consumption * Energy\_use\_rate\_\_for\_water\_treatment)$
Description	It represent the annual electric-energy used for water treatment at treatment plants.
Initial Value	Not applicable
Reference for definition of independent variables	
$Annual\_Water\_Consumption$	Object A2.8
$Energy\_use\_rate\_\_for\_water\_treatment$	Object A4.10

A 4.17 $Annual\_Energy\_used\_for\_water\_distribution$

Type	Flow
Unit	Mega joule per year
Equation	$Annual\_\_energy\_used\_for\_water\_treatment = (Annual\_Water\_Consumption * Energy\_use\_rate\_\_for\_water\_treatment)$
Description	It represent the annual electric-energy used for water treatment at treatment plants.
Initial Value	Not applicable
Reference for definition of independent variables	
$Annual\_Water\_Consumption$	Object A2.8
$Energy\_use\_rate\_\_for\_water\_distribution$	Object A4.8

A 4.18 $Annual\_Energy\_use\_for\_sewage\_collection$

Type	Flow
Unit	Mega joule per year
Equation	$Annual\_Energy\_use\_\_for\_sewage\_collection = AnnualTotal\_Sewage\_Flow * Energy\_use\_rate\_for\_sewage\_pump)$
Description	It represent the annual electric-energy used for pumping wastewater at sewer system.
Initial Value	Not applicable
Reference for definition of independent variables	
$AnnualTotal\_Sewage\_Flow$	Object A1.19
$Energy\_use\_rate\_\_for\_sewage\_pump$	Object A4.7

A 4.19 $Annual\_Energy\_used\_for\_sewage\_treatment$

Type	Flow
Unit	Mega joule per year
Equation	$Annual\_Energy\_used\_for\_sewage\_treatment = Energy\_use\_rate\_\_for\_sewage\_treatment * AnnualTotal\_Sewage\_Flow)$
Description	It represent the annual electric-energy used for pumping wastewater at sewer system.
Initial Value	Not applicable
Reference for definition of independent variables	
$AnnualTotal\_Sewage\_Flow$	Object A1.19
$Energy\_use\_rate\_\_for\_sewage\_treatment$	Object A4.6

A 4.20 $Energy\_used\_for\_sewage\_treatment$

Type	Stock
Unit	Mega joule
Equation	$Energy\_used\_\_for\_sewage\_treatment(t) = Energy\_used\_\_for\_sewage\_treatment(t - dt) + (Annual\_Energy\_used\_for\_sewage\_treatment) * dt$
Description	It represent the total electric-energy used for pumping wastewater at sewer system during the life cycle of the WWC system.
Initial Value	0
Reference for definition of independent variables	
$Annual\_Energy\_used\_for\_sewage\_treatment$	Object A4.19

A 4.21 $Energy\_used\_for\_water\_distribution$

Type	Stock
Unit	Mega joule
Equation	$Energy\_used\_for\_water\_distribution(t) = Energy\_used\_for\_water\_distribution(t - dt) + (Annual\_energy\_used\_for\_water\_distribution) * dt$
Description	It represent the total electric-energy used for pumping water at water distribution system during the life cycle of the WWC system.
Initial Value	0
Reference for definition of independent variables	
$Annual\_energy\_used\_for\_water\_distribution$	Object A4.17

A 4.22 $Energy\_used\_for\_sewage\_collection$

Type	Stock
Unit	Mega joule
Equation	$Energy\_used\_for\_sewage\_collection(t) = Energy\_used\_for\_sewage\_collection(t - dt) + (Annual\_Energy\_use\_\_for\_sewage\_collection) * dt$
Description	It represent the total electric-energy used for pumping wastewater at sewer system during the life cycle of the WWC system.
Initial Value	0
Reference for definition of independent variables	
$Annual\_Energy\_used\_for\_sewage\_collection$	Object A4.18

A 4.23 $Energy\_used\_for\_water\_treatment$

Type	Stock
Unit	Mega joule
Equation	$Energy\_used\_for\_water\_treatment(t) = Energy\_used\_for\_water\_treatment(t - dt) + (Annual\_\_energy\_used\_for\_water\_treatment) * dt$
Description	It represent the total electric-energy used for pumping water at water distribution system during the life cycle of the WWC system.
Initial Value	0
Reference for definition of independent variables	
$Annual\_energy\_used\_for\_water\_treatment$	Object A4.16

A 4.24 $Annual\_GHG\_Emission\_from\_Electricity\_use$

Type	convertor
Unit	Mega joule per year
Equation	$Annual\_GHG\_Emission\_from\_\_Electricity\_Use = (Annual\_Energy\_used\_for\_sewage\_treatment + Annual\_energy\_used\_for\_water\_distribution + Annual\_Energy\_use\_\_for\_sewage\_collection + Annual\_\_energy\_used\_for\_water\_treatment) * Convert\_\_MJ\_to\_KWh * GHG\_EF\_\_Ontario\_Electricity$
Description	It represent the annual total GHG emission resulted from electric-energy generation in Ontario which is used in operation of water and wastewater infrastructure systems.
Initial Value	Not applicable
Reference for definition of independent variables	
$Annual\_energy\_used\_for\_water\_distribution$	Object A4.17
$Annual\_energy\_used\_for\_water\_treatment$	Object A4.16
$Annual\_energy\_used\_for\_sewage\_collection$	Object A4.18
$Annual\_energy\_used\_for\_sewage\_treatment$	Object A4.19
$Convert\_\_MJ\_to\_KWh$	Object A4.11
$GHG\_EF\_\_Ontario\_Electricity$	Object A4.9

A 4.25 $Annual\_total\_GHG\_emission$

Type	Flow
Unit	Kg CO2 per year
Equation	$Annual\_total\_GHG\_Emisison = Annual\_GHG\_Emission\_from\_\_Electricity\_Use + Annual\_GHG\_Emission\_from\_\_rehabilitation + Annual\_GHG\_emission\_from\_\_replacement\&new\_pipe\_\_instalation + Annual\_GHG\_Emission\_\_for\_sewage\_treatment\_\_processes$
Description	It represent the annual total GHG emission resulted from WWC asset management scenario.
Initial Value	Not applicable
Reference for definition of independent variables	
$Annual\_GHG\_Emission\_from\_\_Electricity\_Use$	Object A1.24
$Annual\_GHG\_Emission\_from\_\_rehabilitation$	Object A4.14
$Annual\_GHG\_emission\_from\_\_replacement\&new\_pipe\_\_instalation$	Object A4.12
$Annual\_GHG\_Emission\_\_for\_sewage\_treatment\_\_processes$	Object A4.15

A 4.26 $Total\_GHG\_Emission$

Type	Stock
Unit	Kg CO2
Equation	$Total\_GHG\_Emission(t) = Total\_GHG\_Emission(t - dt) + (Annual\_total\_GHG\_Emisison) * dt$
Description	It represent the total GHG emissions resulted from WWC asset management scenario for the whole life cycle of the WWC system.
Initial Value	0
Reference for definition of independent variables	
$Annual\_total\_GHG\_Emisison$	Object A4.25