Sustainable Municipal Water and Wastewater Management Using System Dynamics

by

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AUTHOR'S DECLARATION

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

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

Abstract

The overall goal of this research is to develop an integrated system dynamics framework for sustainable management of municipal water and wastewater systems. Canadian municipalities have traditionally relied on grants received from senior levels of government to finance construction of water supply and wastewater collection infrastructure. User fees for water and wastewater services were determined so as to recover only the operating expenditures with no allowance to recoup the capital costs of infrastructure. As the infrastructure assets started approaching the end of their service life, investments needed to rehabilitate these assets were deferred in the expectation of receiving further grants for this purpose. Hence, a significant backlog of deteriorated infrastructure has accumulated over the years. Recently enacted regulations require that all expenditures incurred on provision of water and wastewater services should ultimately be financed from user fee based revenues. Another piece of legislation provides for establishment of service performance standards.

Urban water and wastewater systems involve interconnections among physical infrastructure, financial, and socio-political factors. Several interacting feedback loops are formed due to these interconnections and render the management of water and wastewater infrastructure as a complex, dynamic problem. Existing asset management tools in the literature are found inadequate to capture the influence of feedback loops. A novel system dynamics approach is used to develop a demonstration model for water and wastewater network management. Model results for a case study show significance of feedback loops for financial sustainability of the system. For example, user fees have to be substantially increased to achieve financial sustainability, especially when price elasticity of water demand is considered.

A detailed causal loop diagram for management of wastewater collection networks is presented. The causal loop diagram lays out qualitative causal relationships among system components and identifies multiple interacting feedback loops. Based on this causal loop diagram, a system dynamics model comprised of a wastewater pipes sector, a finance sector, and a consumers sector, is developed. Policy levers are included in the model to facilitate formulation of different financing and rehabilitation strategies for the wastewater collection network. Financial and service performance indicators included in the model allow comparison of different financing and rehabilitation strategies. Data requirements for implementation of the model are discussed.

The wastewater collection network model is implemented for a case study of a medium-sized Canadian municipality with a substantial backlog of deteriorated pipes. A methodology for parameterization of the model using existing data sources is presented. Simulation results indicate that different financing strategies ranging from no borrowing to full utilization of debt capacity can achieve similar total life-cycle costs but with significantly varying impacts for consumers in terms of service performance and financial burden.

A detailed causal loop diagram for management of a watermain distribution network is employed to identify feedback loops. The causal loop diagram is then developed into a system dynamics model comprised of watermain pipes, financial, and consumer sectors. Data requirements for implementation of the model are discussed.

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Dedication

To my parents, my wife, my children, and my siblings.

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Chapter 1

Introduction

1.1 Background

Supply of clean drinking water and efficient disposal of wastewater are essential to maintaining a high quality of life and promoting economic activity in a modern city. Reliable provision of these services requires installation, operation and maintenance of expensive infrastructure including water abstraction and treatment facilities, storage reservoirs, watermain distribution networks, pumping stations, wastewater collection networks and treatment plants. The value of these infrastructure assets in Ontario is estimated to be $72 billion (Swain et al., 2005). The earliest water and wastewater systems in Ontario were constructed around the middle of nineteenth century. However, extension of these services across the province really picked up in pace in the period following the World War II, and by 1983, 98% of Ontario's urban population had received coverage (Strategic Alternatives, 2001). This rapid expansion was made possible by the grants that municipalities received from the federal and provincial governments. However, the generous grants also encouraged municipal governments to install infrastructure systems with unnecessarily large capacity (Swain et al., 2005). Furthermore, user fees for water and wastewater services were designed so as to recover only the operating expenditures incurred on these services (Renzetti, 1999). In general, no proactive measures were undertaken to recover capital costs so that adequate resources would be available to finance the impending replacement/rehabilitation of the ageing infrastructure. This approach was to some extent motivated by the expectation of continuing flow of grants from the senior levels of government (Brubaker, 2011). During the 1990s, municipal governments in Ontario were transferred the responsibility for additional services from the province. Amongst the competing demands on the financial resources of municipalities, water and wastewater infrastructure often received inadequate attention of decision makers due to the 'less visible' nature of these assets (Brubaker, 2011). By the turn of the century, the consequences of this neglect started becoming apparent in many communities in the form of frequent watermain bursts, sewer backups and floodings, and discoloured water events. And, researchers drew the attention of policy makers towards the accumulating backlog of deferred maintenance (Mirza and Haider, 2003).

However, just as some of the earliest water systems were constructed only after disasters had struck[1], it took a tragedy to act as a catalyst for change in the status quo. In May 2000, as a result of a contaminated water supply in the town of Walkerton, Ontario, seven people died and more than 2300 became seriously ill. Besides the tragic human suffering, the economic impact of the incident alone is estimated at $64.5 million (Livernois, 2002). Based on the recommendations contained in the Walkerton Inquiry Commission report (O'Connor, 2002), several regulations have since been enacted in the Province of Ontario. These regulations mark a paradigm shift in the way that municipal water and wastewater systems are managed in Ontario. The regulations issued under the authority of the Safe Drinking Water Act 2002 establish licensing requirements for municipal water systems, require training and certification of operators and water quality analysts, prescribe drinking water quality standards, and stipulate preparation of financial plans (Ministry of the Environment, 2002). Specifically, Ontario Regulation 453/07 requires municipalities to prepare financial plans for a period of at least six years and include details such as total financial assets, non-financial assets that are tangible capital assets, projected total revenues, total expenses, annual surplus or deficit, and accumulated surplus or deficit (Ministry of the Environment, 2007a). An important guiding principle for the preparation of financial plans is that water and wastewater systems should be financially self-sustainable (Ministry of the Environment, 2007b). This means that all costs incurred on the provision of water and wastewater services should ultimately be financed from the user fee-based revenues of these services. It should be noted that Ontario municipalities were allowed to finance water works projects from user fees as early as 1943 (Strategic Alternatives, 2002), but as mentioned above this authority was not actually exercised. Ontario Regulation 453/07 is thus intended to redress this situation.

The more recent legislation, Water Opportunities and Water Conservation Act 2010, reiterates the requirement of financial sustainability plans for water and wastewater systems and in addition requires preparation of an asset management plan for physical infrastructure, a water conservation plan, and a risk assessment and mitigation plan. This act also empowers the Minister of the Environment to establish and monitor progress towards financial, operational and maintenance, and water conservation performance targets (Ministry of the Environment, 2011).

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[1] For example, improvements in water supply systems of Kingston (1849) and Hamilton (1854) were made following an outbreak of cholera and a series of fire incidents, respectively (Strategic Alternatives, 2001).

In addition to the above mentioned regulations, a recent change in the accounting standards also impacts Canadian municipalities. The Canadian Institute of Chartered Accounts (CICA) Public Sector Accounting Board statement PS3150 now requires municipal governments to report all tangible capital assets along with their depreciation on financial statements (CICA, 2007).

1.2 Problem Statement and Motivation

To the extent that available financial resources need to be optimally utilized for maintaining water and wastewater systems at acceptable levels of service, the problem is similar to that of other public infrastructure assets such as roads, bridges, and public buildings. The concept of infrastructure or asset management that has evolved as a solution to the problem (Hudson et al., 1997) is thus also common to these various infrastructure assets. Stated broadly, asset management seeks to combine engineering knowledge with sound economic and financial practices (Federal Highways Administration, 1999). A few recent developments in asset management systems for water and wastewater infrastructure include: relational databases for registration, integration and analysis of data (Younis, 2010; Halfawy and Figueroa, 2006), tools for assessment and condition grading of infrastructure components (Costello et al., 2007; Rizzo, 2010), models for predicting remaining service life of infrastructure assets (Berardi et al., 2008; Savic, 2009; Younis and Knight, 2010a,b; Ana and Bauwens, 2010), and prioritization schemes and optimization strategies for rehabilitation of assets (Moglia et al., 2006; Dandy and Engelhardt, 2006; Saegrov, 2005,2006).

Municipal water and wastewater systems have peculiar characteristics, especially when considered within the context of financial self-sustainability. Specifically, management of these infrastructure assets constitutes an integrated system wherein technical elements of the system (as noted above) are interconnected with the financial and social elements. Such interconnections are briefly summarized below.

Water and wastewater services are essential public services and hence any price-setting exercise invariably involves a consideration of affordability. Even when affordability is not a cause of concern, customers still expect user fee changes (increases) to be gradual and justifiable. When ownership of the water and wastewater utility lies in the public sector, user fee changes need approval from a municipal council or a board including elected officials. This implies that the utility is constrained in setting user fees and hence its revenue generation capacity. This constraint is especially significant for a utility mandated to operate as a self-financing entity.

Service performance of a utility depends upon the capital investments made to maintain structural and operational integrity of the infrastructure. To achieve and maintain desired performance levels, investments have to be stable and adequate. Various approaches can be adopted for financing long-term capital investments including “pay-as-you-go” whereby current revenues are utilized for capital expenditures, building up reserve funds and utilizing them as needed, and borrowing. Each (or a combination) of these approaches has different implications for required user fee levels and intergenerational equity. Moreover, service performance levels (depending upon the backlog of deferred maintenance) and total life-cycle costs of operating the infrastructure can be significantly different.

Consumption of water and generation of wastewater depends upon the price signals that consumers receive. Any adjustments that the consumers make in their usage patterns impact the utility’s revenues and hence its ability to finance its operational and capital expenditures.

The technical, financial, and social elements involved in the management of water and wastewater systems do not remain static but rather evolve over time. For example, customers’ willingness to accept user fee hikes depends upon the prevailing user fee value, the ease and cost of adjusting water demand, and service performance levels. An important feature of water and wastewater infrastructure management is that the interconnections between the various system components often result in feedback loops. Existence of multiple interacting feedback loops imparts complexity to the system (Sterman, 2000). Currently available decision support tools are not adequate to account for the dynamic (evolving over time) and complex (due to feedback loops) characteristics of water and wastewater infrastructure management. To properly understand system behaviour, a holistic framework is needed that integrates physical, financial, and social elements of the system.

1.3 Research Objectives

The overall goal of this research is to present a framework for the management of financially self-sustaining municipal water and wastewater systems. This goal is achieved by pursuing the following specific research objectives:

1. Graphically illustrate interconnections between system components and establish existence of feedback loops involved in the management of municipal water and wastewater systems.
2. Demonstrate the significance of feedback loops for long-term financial sustainability of watermain distribution and wastewater collection networks management.

3. Develop decision support models (one each) for management of municipal wastewater collection networks and watermain distribution networks which integrate their respective physical, financial, and consumer sectors. The models should include policy levers (to allow formulation) and performance indicators (to enable comparison), of alternative financing and rehabilitation strategies.
4. Identify existing data sources that can be used to parameterize the developed decision support models.
5. Explore the trade-offs between different management strategies in terms of financial and service performance indicators using a case study of an urban wastewater collection network.

1.4 Thesis Organization

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

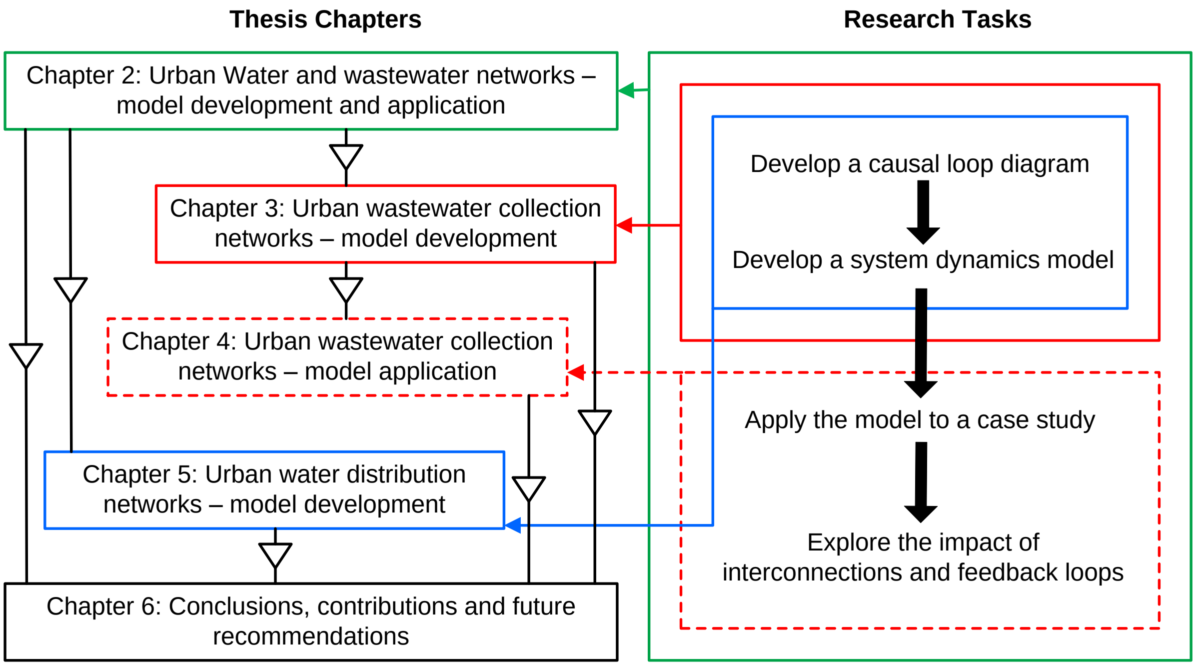

Figure 1.1: Flow chart of thesis chapters and research tasks.

Chapter 2 presents a high level integrated model for watermain distribution and wastewater collection networks. With limited scope and incorporating only a few feedback loops, a system dynamics model is developed to demonstrate the significance of feedback loops for financial management of a typical Canadian water utility. Model results are used to make the case for more a more complete utility model.

In Chapter 3, a detailed causal loop diagram is presented that identifies feedback loops related to the management of municipal wastewater collection networks. Based on the qualitative causal loop diagram, a system dynamics model is developed and data requirements for the model are discussed. Use of policy levers and performance indicators for formulation and evaluation of management strategies is also explained.

Chapter 4 describes implementation of the wastewater collection network management model developed in Chapter 3. A medium-sized Canadian city with a large backlog of deteriorated wastewater pipes is used as a case study. A methodology is presented for parameterization of the model using available utility data. Trade-offs between alternative financing strategies, ranging from a strict ‘zero funds balance’ with no borrowing to utilization of maximum debt capacity, are explored.

A detailed causal loop diagram and system dynamics model for management of municipal watermain distribution networks are presented in Chapter 5. Similar to the Chapter 3, data requirements, policy levers, and performance indicators for the watermains network model are discussed. A general summary of conclusions and recommendations for the future are presented in Chapter 6.

Chapter 2

Application of system dynamics for developing financially self-sustaining management policies for water and wastewater systems[2]

2.1 Introduction

In this chapter, management of water and wastewater networks is shown to be a complex system with multiple interconnections and feedback loops. This is accomplished by developing a causal loop diagram for a financially self-sustaining water utility. The novel system dynamics approach is used to develop a demonstration model for water and wastewater network management. Results of the demonstration model highlight the significance feedback loops, thus making the case for more complete utility models which are presented later in Chapters 3, 4 and 5.

Municipal water and wastewater systems deliver clean water to residents, businesses, and industries and collect contaminated water (wastewater) for treatment and disposal. The health and prosperity of cities depend on well-functioning "out of sight" and often "out of mind" water and wastewater networks. In North America the assigned service life of buried distribution and collection pipeline is often 50 to 75 years (Ministry of the Environment, 2007b; Congressional Budget Office, 2002) even though in some cases these pipes have been in service for more than 100 years. In North America, many cities are faced with the challenge of managing aging water and wastewater infrastructure with limited fiscal and personnel resources while ensuring that adequate levels of service are provided to consumers and customers.

In Canada, recent federal and provincial government legislation requires public water agencies to be financially accountable by mandating new reporting requirements. New regulations include the Canadian Institute of Chartered Accountants Public Sector Accounting Board (PSAB) statement PS3150 that requires all municipalities, starting in January 2009, to report all tangible capital assets along with their depreciation on financial statements (CICA, 2007) and Province of Ontario Regulation 453/07 (Ministry of the Environment, 2007a), developed under the Safe Drinking Water Act that requires all public utilities prepare and submit yearly reports on the current and estimated future condition of water and wastewater infrastructure. The later also requires the preparation and

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[2] A version of this chapter has been published as Rehan et al. (2011).

publication of long-term water and wastewater sustainability financial plans. This is related to the concept of “sustainable urban water” emerging in other parts of the world. A key principle for these plans is that revenues should be sufficient to pay all expenses of providing services (Ministry of the Environment, 2007b). In the United States, the Governmental Accounting Standards Board (GASB) Statement 34, in France Accounting Standard M49, and in Australia, the Australian Accounting Research Foundation Standard 27 specifies similar accounting practices to PSAB (see Federal Highways Administration, 2000; Howard, 2001; and Barraque and Le Bris, 2007).

Over the past several years many researchers have developed decision support tools to aid water utilities manage their water and wastewater networks. These tools include some or a combination of activities such as: registration of data related to infrastructure components; assessment and grading of the asset conditions; analysis of data for predicting remaining service life; comparison of costs of repair/rehabilitation alternatives over their life cycles; and, prioritization of rehabilitation activities that ensure maximum benefits at minimum costs (Grigg, 2003).

The following provides an overview of management tools developed for water distribution networks. Shamir and Howard (1979) developed one of the first age based models to predict watermain failure rates and Deb et al. (1998) developed the KANEW model using the concept of a survival function, which is a statistical predictor of useful life of a group of pipes belonging to the same class (e.g. age, material, and diameter). Kleiner et al. (1998b) modelled the performance of a water distribution network by incorporating both the deterioration of structural integrity and hydraulic capacity. This approach is used to identify optimal rehabilitation strategies that minimize the total costs of rehabilitation and all maintenance over the planning horizon. Hadzilacos et al. (2000) present a prototype decision support system (DSS) called UtilNets for water pipes. This model facilitates rehabilitation of critical watermains based on reliability based life predictions. The DSS provides an aggregate structural, hydraulic, water quality, and service profile of a network along with an assessment of the required rehabilitation expenditures. Burn et al. (2003) employ a non-homogeneous Poisson burst count model for predicting failure rates of pipes and developed PARMS-PLANNING which analyses expenditures and costs over a range of strategies. Moglia et al. (2006) developed PARMS-PRIORITY to add calculations for risk, failure predictions, cost assessment, scenario evaluation, and data exploration. In Saegrov (2005), KANEW is developed into CARE-W, a more comprehensive DSS that has modules for the assessment of performance indicators, prediction of pipe failures, and water supply reliability. Results generated from these modules are utilized in two further modules that allow for planning long-term investment needs and annual rehabilitation project selection and ranking. Giustolisi et al. (2006) developed a polynomial regression method to predict the burst rates of watermains. The policy option explored is comparison of the reduction in burst rates after pipes' replacement versus the cost of replacement. Dandy and Engelhardt (2006) applied a multi-objective genetic algorithm approach to develop trade-off curves between economic cost and reliability for replacement schedules of water pipes. Tabesh et al. (2009) present artificial neural network and neuro-fuzzy system models. This study found the artificial neural network model superior in terms of predicting pipe failure rate and for the assessment of mechanical reliability in water distribution networks. Kleiner et al. (2010) present a pipe failure prediction model and optimize renewal investments by taking into account costs that include adjacent infrastructure and economies of scale.

The development of wastewater (sewer) network management tools is discussed in the following section. Wirahadikusumah and Abraham (2003) use probabilistic dynamic programming in conjunction with a Markov chain model to perform life cycle cost analysis of sewers. Savic et al. (2006) use evolutionary polynomial regression to develop models for predicting wastewater blockage events and collapse failures. Saegrov, (2006) develops CARE-S, a corresponding framework to CARE-W for wastewater network rehabilitation decision making. CARE-S is a comprehensive DSS that combines several tools relevant to wastewater infrastructure management into a single platform. Younis and Knight (2010a) present a continuation ratio model that can be used for risk-based policy development for maintenance management of wastewater collection systems. Their proposed model can be used in devising appropriate intervention plans and optimum network maintenance management strategies based on pipelines age, material type, and internal condition grades. Younis and Knight (2010b) show that a cumulative logit model can be used to determine wastewater pipelines' service life, predict future condition states, and estimate networks' maintenance and rehabilitation expenditures.

Halfaway et al. (2006) reviewed the following commercial municipal asset management systems: Synergen, CityWorks, MIMS, Hansen, RIVA, Infrastructure 2000, and Harfan. They found the majority of existing commercial asset management software to focus on operational management (e.g., work orders, service requests) with little or no functionality to support long-term renewal planning decisions (e.g., deterioration modelling, risk assessment, life cycle cost analysis, asset prioritization). From the reviewed systems, RIVA, Harfan, and Infrastructure2000 implemented some level of support for long-term renewal planning of specific assets, mainly pavement. The other four systems included condition assessment and rating modules. Most of these commercial software tools now incorporate PSAB and other legislation annual reporting requirements and have improved strategic long range asset, risk and budget management by forecasting the full lifecycle of infrastructure assets. They also generate a lifecycle cost and risk profile for each asset, determine the events that should be scheduled each period, as well as, the impact on cost, condition, risk and capacity. None of these tools are water and wastewater asset specific management tools.

Currently, no integrated water and wastewater decision support tool exists that considers the impact of feedback loops and complex interactions between integrated water, wastewater, financial and social sectors. Englehardt et al. (2003) state that when considering the financial sustainability of a water utility, it is vital to include the whole life cycle costs associated with network operation, maintenance, and rehabilitation. Linerand and deMonsabert (2010) indicate that the application of the triple bottom line (TBL) also requires utilities to analyze alternatives to address conflicting goals of economics (financial), environmental, and social issues.

This study proposes a novel interconnected municipal water and waste water asset management framework using a system dynamic model. This management framework will assist water utilities in whole life cycle cost analysis and to address triple bottom line principles.

In this chapter, first the complex interconnections and feedback loops between the physical infrastructure, financial and consumer sectors, are demonstrated. Then the use and application of system dynamics modeling for integrated water and wastewater network pipeline asset management is described. This is the first known application of system dynamics to self-sustaining water and wastewater asset management. This is then followed by the development of a basic aggregated water and wastewater system dynamics demonstration model that is used to model the significance of complex interconnections and feedback loops on management decisions. A fully integrated water and wastewater model can be developed that includes water and wastewater pipe network, access chambers (manholes), laterals, valves, hydrants, and treatment plants, using the proposed system dynamics approach. Burnside (2005) noted that water distribution and wastewater collection networks together constitute approximately 75 percent of the costs of a municipal water system. Since water distribution and wastewater collection networks account for the majority of the utility costs, the cost of water and wastewater treatment is not considered in this chapter analysis.

The demonstration system dynamics model is then used to show the impact of three specific management strategies on the utilities' financial sustainability over the long-term. Three specific scenarios are discussed. First, the utility is assumed to under invest in the water distribution and wastewater collection networks by not paying for capital works needed to replace deteriorated buried pipes. Second, the utility is assumed to adopt a 1% annual replacement rate strategy. This strategy is motivated by the assumption that the average pipe lifespan is 100 years. Therefore, the entire network will be effectively replaced once every 100 years. Third, the utility is assumed to adopt a strategy by which no more than 5% of its network is in the poorest condition state. For each of the above three scenarios, three variations are considered which reflect: (A) a constant user fee and with no constraints on the utility's fund balance, i.e. revenues do not need to equal expenses; (B) a variable user fee and with a zero funds balance, i.e. revenues equal expenses; and (C) a variable user fee, zero funds balance and price elasticity of water demand.

2.2 Modelling the Complexity of Water and Wastewater Network Management

The concept of interconnected components and complex system behaviour for urban water systems is well recognized. For example, Grigg and Bryson (1975) presented a simulation model that is comprised of four interconnected sectors – financial accounting, water balance, water use, and population growth. Kotz and Hiessl (2005) demonstrated dynamic system interdependencies and used an agent-based modeling approach to simulate technical innovation processes in these systems. Guest et al. (2010) studied interactions among sustainability aspects related to decentralized wastewater treatment systems using a qualitative system dynamics approach. Ahmad and Prashar (2010) also use a system dynamics model to study interconnections among population growth, land use changes, water demand, and water availability. Adeniran and Bamiro (2010) modelled the interconnections among Finance, Production, Distribution, and Operation & Maintenance sectors of a municipal water supply system. This model does not include water and wastewater physical infrastructure.

Management of municipal water and wastewater networks is a complex problem. Sterman (2000) states that the interaction of feedback loops is responsible for complex system behaviour. When a component inside a feedback loop is changed, the perturbation traverses along the loop resulting in a change to the originating component (Hannon and Ruth, 1994). When a change in the originating component causes a change in other components that strengthens the original process, the feedback loop is termed a positive or a self-reinforcing loop. If the response of other components along the loop counteracts the original change, a negative or balancing loop is deemed to exist (Hannon and Ruth, 1994).

In this section, feedback loops related to water and wastewater network management are identified using Figure 2.1 causal loop diagram (CLD). In a CLD, relationships between variables are depicted using arrows with a positive (+) or negative (-) sign placed besides the arrow head to indicate link polarity. A positive link polarity implies that "*if a cause increases, the effect increases above what it would otherwise have been*" and vice versa (Sterman, 2000). Similarly, a negative link polarity "*means that if the cause increases, the effect decreases below what it would otherwise have been*" and vice versa (Sterman, 2000).

A simplified CLD for municipal water and wastewater network management is shown in Figure 2.1. Names of feedback loops are in bold font and thick curved arrows around loop names indicate the direction of causation. The objective of presenting the CLD in Figure 2.1 is to frame the scope of the system dynamics model that is developed as part of this research. The system dynamics model that is presented later in this work implements only a subset of the Figure 2.1 causal loops. The "bigger picture" of what major causal loop dependencies exist within a water and wastewater network from a management perspective is described. For this chapter, discussion is limited to causal loops that illustrate sustainable financial management strategies and demonstrate complexity of the system.

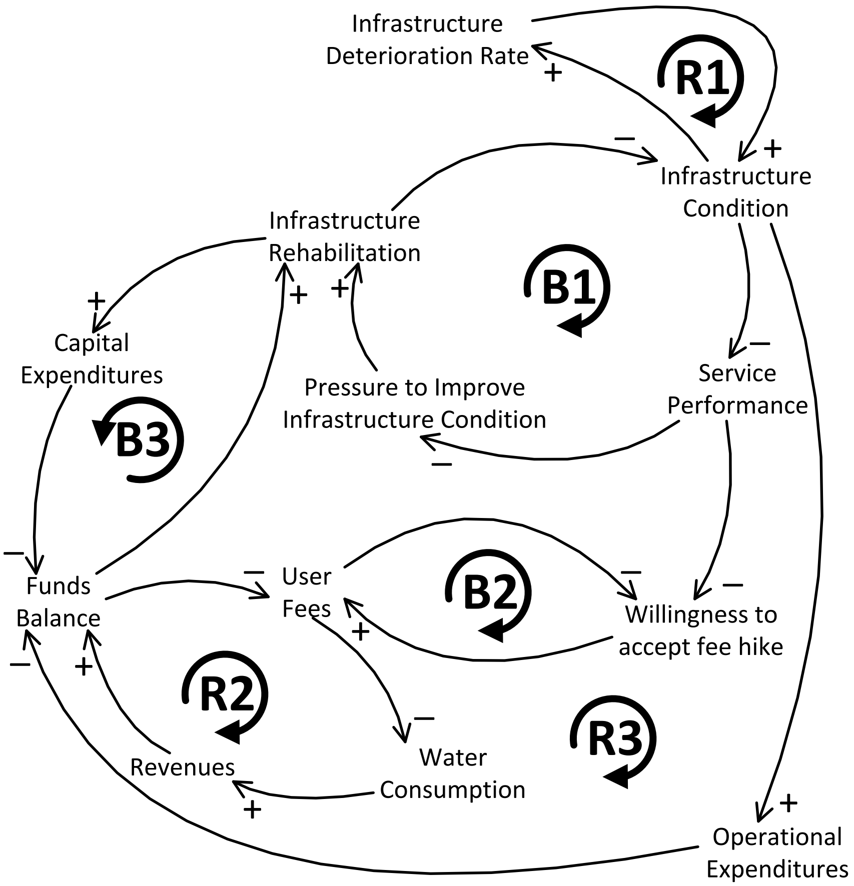


Figure 2.1: Feedback loops in water and wastewater network management.

2.2.1 Feedback loop in infrastructure deterioration (R1)

Reinforcing loop R1 (Figure 2.1) represents the typical deterioration process for physical infrastructure. It shows that the rate of deterioration of infrastructure is a function of its existing condition, which in turn, determines the condition of the infrastructure. If the condition of an infrastructure component increases (e.g., on a scale of 1-5, where 5 is a poor state and 1 is the best state), an increase in the deterioration rate occurs. A higher deterioration rate then leads to further deterioration of the infrastructure. Thus, a cycle is established in which infrastructure deterioration occurs at an accelerated rate. Wirahadikusumah and Abraham (2003) report a similar process of deterioration.

2.2.2 Feedback loop in infrastructure rehabilitation (B1)

The exponential deterioration of infrastructure caused by loop R1 is mitigated by a balancing loop, B1. If infrastructure condition deteriorates (increases), the network's service performance will decline as a result. For example, deteriorated watermains cause more discoloured water events and watermain breaks. Similarly, reduced hydraulic capacity of deteriorated wastewater pipes will result in frequent backups. Increased complaints by consumers due to poor service performance of watermain and wastewater pipes will increase pressure on utility managers to improve the infrastructure condition by employing rehabilitation techniques. Increased rehabilitation works translate into improved infrastructure condition, closing the loop. Thus, deterioration in infrastructure condition, in a functional society, will ultimately drive improvement.

2.2.3 Feedback loop in revenue generation (R2)

A water utility is financially self-sustaining when its revenues equal or exceed its expenses. When its fund balance (revenues minus expenditures) falls below a threshold value, the utility will often increase revenues by increasing user fees. Consumers can respond to an increase in user fees by reducing water consumption. The reduction in water use is often characterized by time delays (Fortin et al., 2002). For the more prevalent case where the utility charges its customers on the basis of consumed volume of water, a decrease in water consumption will reduce revenues. Lower revenues will result in a decreased fund balance. A self-reinforcing loop is established where an initial rise in user fees will ultimately cause user fees to increase more. It should be noted that this self-reinforcing feedback loop may not operate indefinitely as constraints on one or more parameters around the loop may be triggered that stop growth. For instance, once the minimum water demand (due to social or technological limits) is reached, further decreases may not occur regardless of user fees increases.

2.2.4 Feedback loop in user fees adjustments (B2)

The operation of reinforcing loop R2 can be constrained by the existence of a balancing feedback loop B2. This feedback loop represents the limitations imposed by the socio-political environment on utility managers. In Canada, urban water and wastewater systems are publically owned. Therefore, user fees increases have to be approved by municipal councils which are sensitive to voters' feedback. When user fees are increased, it causes a reduction in customers' willingness to accept a further fee hike. Reduced willingness to accept a fee hike implies that future user fees will be lower than what would otherwise have been.

Loop B2 is connected to loop B1 through the willingness to accept a fee hike. MacDonald et al. (2003) report that consumers are willing to pay positive amounts of money in return for a water supply service that would be more reliable and less prone to service interruptions. Since a deteriorated infrastructure system will cause increased service interruptions, it is reasonable to suggest that increased deterioration will increase consumers' willingness to accept a fee hike. An increased willingness to accept a fee hike will result in increased user fees.

2.2.5 Feedback loop in capital expenditures (B3)

Increased rehabilitation of infrastructure will increase the utility's capital expenditures. This in turn reduces the availability of funds for further rehabilitation works. With a lower fund balance, infrastructure rehabilitation is decreased.

2.2.6 Feedback loop in operational expenditures (R3)

This feedback loop is comprised of the following variables: Infrastructure Condition, Operational Expenditures, Fund Balance, and Infrastructure Rehabilitation. When the infrastructure condition deteriorates (increases), operational expenditures will increase due to the need for more frequent pipe flushing and emergency repairs. Pumping costs (due to reduced hydraulic capacity) will also increase. Deteriorated condition is also associated with water leakage in case of watermains and infiltration in case of sanitary sewers. Both these scenarios entail additional costs for the utility. An increase in operational expenditures will lower the funds balance and in turn the funds available for rehabilitation. With less rehabilitation, the condition of infrastructure will deteriorate further resulting in the cycle of deterioration to accelerate.

The above discussion shows that water and wastewater infrastructure management involves multiple interacting feedback loops. To date, no model is available that captures the dynamic complexity arising due to these feedback loops. Therefore, a novel contribution of this study is to develop a system dynamics model that can be used for strategic network management.

2.3 System Dynamics Modelling

System dynamics is a feedback-based object-oriented modeling paradigm developed by Forrester (1958) to model complex systems. The basic building blocks for system dynamics models are: stocks, flows, converters, and connectors (Figure 2.2).

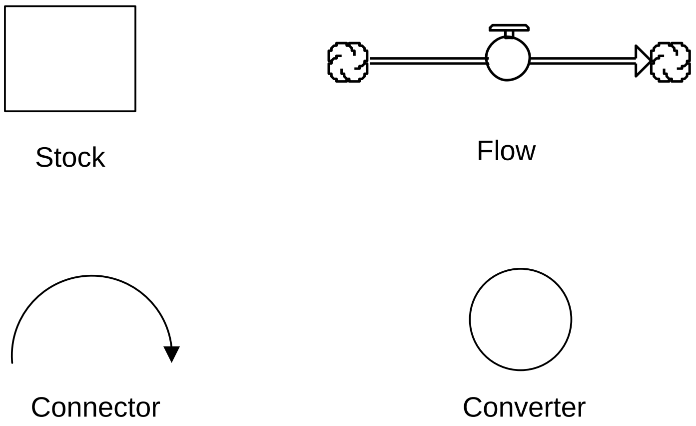


Figure 2.2: Building blocks of system dynamics models.

Stocks represent accumulations - both physical and non-physical. Examples of physical stocks are inventory of pipes, amount of water in a reservoir, etc. A non-physical stock is the consumer's level of satisfaction with a water utility service. Stocks represent the 'traces' left by an activity. Material in a stock exists at a given point in time and persists even when activities end. Flows represent activities or actions in a stock that transport quantities into or out of a stock instantaneously or over time. Examples of flows are daily consumption of water, rate at which pipes move from one condition grade to another, and monthly revenues or expenditures of a utility. Mathematically, the relationship between stocks and flows can be described using the following integral form (Sterman, 2000):

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

where t_o is the initial time, t is the current time, $Stock(t_o)$ is the initial value of the stock, $Inflow(s)$ and $Outflow(s)$ are flow rates into and out of a stock at any time s between the initial time t_o and current time t. $Inflow(s)$ and $Outflow(s)$ have the units of $Stock(t)$ divided by time.

Equation 2.2 determines the net rate of change of a stock with time (Sterman, 2000).

$$d(Stock)/dt = Inflow(t) - Outflow(t) \tag{2.2}$$

Figure 2.3 shows a demonstration system dynamics model for a hypothetical water utility that contains three sectors: physical infrastructure, consumer and finance. In Figure 2.3, the connectors (arrows) establish relationships among various elements of the model and move information as inputs for decisions or actions and converters (circles) house graphical and built-in functions. Examples of converters are pipe deterioration curves and demand curves for water usage.

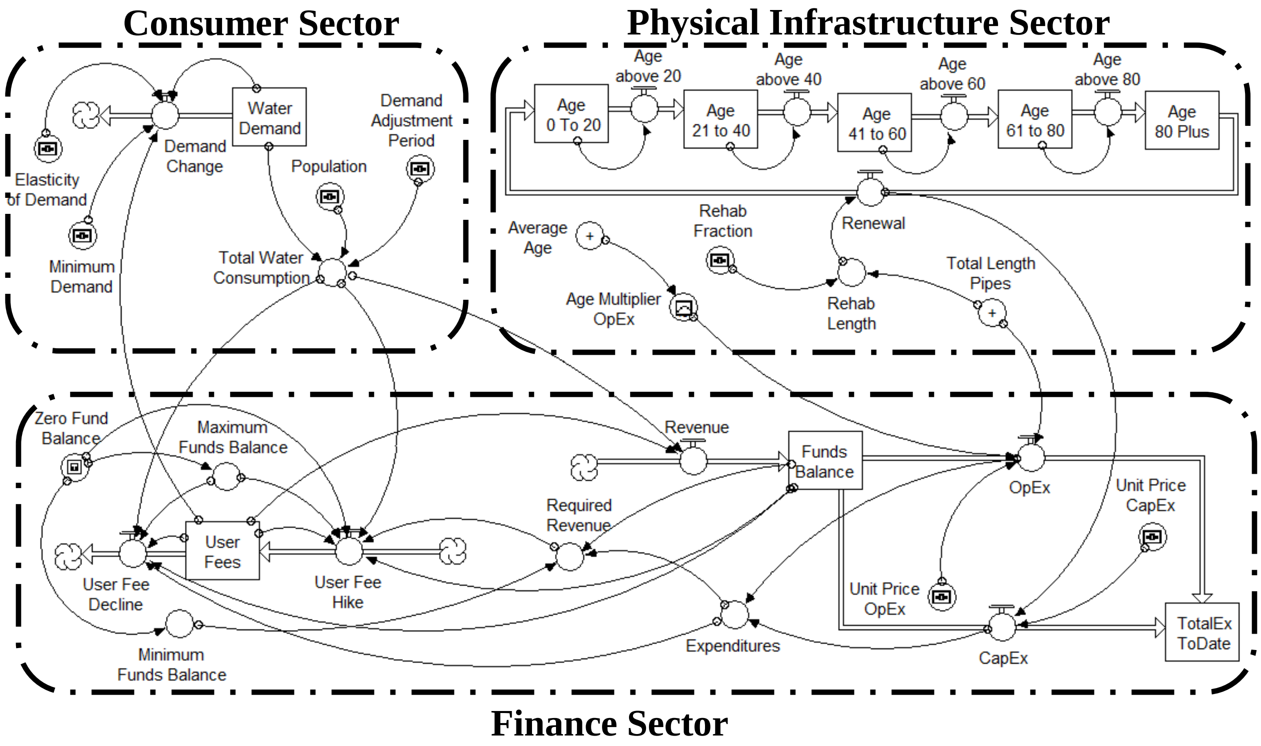


Figure 2.3: Demonstration system dynamics model for a water utility.

2.4 Demonstration System Dynamics Model for Water and Wastewater Network Management

To quantitatively highlight the significance of physical infrastructure, consumer and finance sector interconnections and feedback loops on strategic water utility management decisions the hypothetical demonstration system dynamics model, shown in Figure 2.3, is presented. It should be noted that this demonstration model is not a fully developed water utility model and is not deemed ready for utility management. The presented model is deemed sufficient to make the case for the development of a fully integrated system dynamics model that can be used by utility managers for strategic decision making over the short and long-term. The following sections describe construction of the physical infrastructure, consumer and financial sectors of the demonstration model.

2.4.1 Physical infrastructure sector

The physical infrastructure sector includes water and wastewater network pipes. Although the modelling framework allows for the development of separate water and wastewater pipe stocks, these stocks are aggregated in the demonstration model, for simplicity, into five *Condition Group* stocks ($Condition\ Group\ 20$, $Condition\ Group\ 40$, $Condition\ Group\ 60$, $Condition\ Group\ 80$, and $Condition\ Group\ 100$). Each condition group is assigned an average condition grade using an arbitrary scale that varies from 0 to 100.

Younis and Knight (2010a,b), Tabesh et al. (2009), and Savic et al. (2006) report that the deterioration of watermains and wastewater pipes depends upon several factors and that many different types of deterioration functions can be implemented to represent pipeline deterioration from one condition state to another. In the demonstration model each pipe is allowed to move from one condition state to the next (worse) condition state using flow functions such as $Deterioration\_20to40$, $Deterioration\_40to60$ etc as shown in Figure 2.3. Although, any type of deterioration function can be implemented into $Deterioration$ flows, a simple age-based deterioration function is implemented in the demonstration model - each pipe is allowed to reside in a $Condition\ Group$ stock for an average period of 20 years before moving into the next $Condition\ Group$ stock. The reasons for implementing this simple age-based deterioration process are: 1) age is commonly reported in the published literature to be strongly correlated to pipe condition and 2) the aggregation of the water and wastewater pipe segments into the same $Condition\ Group$

stocks does not allow for the implementation of separate water and wastewater pipeline deterioration functions.

Current Canadian government guidelines (e.g., Ministry of the Environment, 2007b) indicate the service life for various civil infrastructure assets. For wastewater pipelines, the service life ranges from 40 to 75 years with limited or no asset deterioration knowledge (Ministry of the Environment, 2007b). The flexible system dynamics model architecture allows for the pipe average service life to be set to any value. To represent typical Canadian practice, the average service life is set to 100 years.

Pipe renewal and replacement is represented using flow $Renewal$ and user specified input $RehabFraction$. During each simulation time step, flow $Renewal$ moves pipes from stock $Condition\ Group\ 100$ to stock $Condition\ Group\ 20$ using the lesser of $RehabLength$ and the total length of pipes in stock $Condition\ Group\ 100$. Most utilities will have set performance criteria for making rehabilitation investment decisions such as reducing recurring expenditures ($OpEx$) and ensuring levels of service to its customers (minimum service disruptions, watermain breaks, wastewater blockages, adequate water supply pressures, etc). Although performance criteria are not included in the proposed demonstration model, they can be implemented in a fully developed system dynamics model. In the demonstration model poor service levels can be associated with the length of pipes in each $Condition\ Group$ stock as will be explained in Section 2.4.3 below. The current demonstration model is formulated so that all rehabilitation activity only removes pipes from stock $Condition\ Group\ 100$. In practice, existing pipes may be repaired and/or renovated to extend their service life. In a fully developed system dynamics model, pipe repair and renovation activities can be formulated by providing additional flows similar to the flow $Renewal$. For example, if a rehabilitation technique extends the service life of a $Condition\ 80$ pipe by 20 years, then this can be modeled by adding a flow from $Condition\ Group\ 80$ to $Condition\ Group\ 60$.

Converter $RehabLength$ determines the total pipe rehabilitation length and converter $Average\ Condition$ determines the weighted average condition for all network pipes using Equation 2.3.

$$Average\ Condition\ = \frac{\sum_i PipeLengths_i \times i}{\sum_i PipeLengths_i} \tag{2.3}$$

where i is the condition state and is equal to 20, 40, 60, 80 and 100. $PipeLengths_i$ is the length of pipes in condition group i.

2.4.2 Consumer sector

The consumer sector estimates the water demand and use during the simulation period for a constant population. The average daily volume of water consumed per person is determined using stock $WaterDemand$ and flow $DemandChange$. $DemandChange$ is a function of price $ElasticityOfDemand$, $MinimumDemand$ and $UserFees$. Lipsey and Chrystal (1999) define price elasticity of demand as the percentage change in demanded quantity of a good divided by the corresponding percentage change in price. Thus, the function $DemandChange$ decreases $WaterDemand$ if user fees increase. The rationale for the water demand decrease is that consumers will implement water conservation measures (i.e. retrofitting of plumbing fixtures and the installation of water conserving appliances) to reduce water costs as user fees increase. It is also assumed that once water conservation measures are implemented that they will be permanent. Thus, water demand is assumed to remain constant at its minimum attained level even when user fees decrease. Price induced changes in water consumption are not instantaneous and occur over time. As shown in Figure 2.4, a time delay parameter $DemandAdjustmentPeriod$ is implemented using a low initial rate of water consumption change followed by an accelerated rate of change that is followed by a low rate of change. The converter $MinimumDemand$ is used to set a minimum water demand limit. $Total\_Water\_Consumption$ which is the product of population served by the utility and per capita $WaterDemand$, represents the volume of water that is billable and hence earns revenue for the utility. If a large proportion of network is in poor condition, significant volumes of water may be lost due to leakage. In this case the total volume of treated water pumped into the network will be higher than the $Total\_Water\_Consumption$. Additional costs associated with leaked water are included in operational expenditures as explained in the following section.

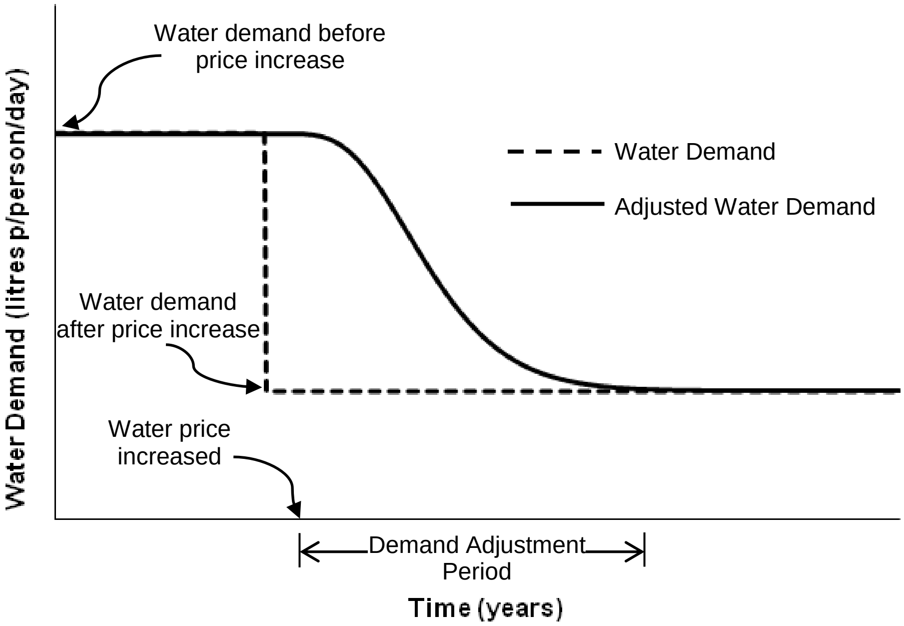


Figure 2.4: Change in water demand implemented over the adjustment period.

2.4.3 Finance sector

The finance sector has two separate but interconnected stock-flow structures - $FundsBalance$ and $UserFees$.

The stock $FundsBalance$ represents the net funds at the end of each simulation time step and is replenished through $Revenue$ inflow. For this analysis a constant volumetric user fee regime is used. The utility's $Revenue$ is calculated by multiplying the water volume consumed during a simulation time step by the user fees. Capital expenditures, $CapEx$, represent rehabilitation costs to move pipes from stock $Condition\ Group\ 100$ (poorest condition state) to stock $Condition\ Group\ 20$ (best condition state). Flow $CapEx$ is calculated by multiplying the length of pipes moving through flow $Renewal$ (physical infrastructure sector discussed in Section 2.4.1 above) and unit price of rehabilitation ($UnitPriceCapEx$, dollars per unit length). Operational expenditures, $OpEx$, represent the cost of unaccounted water loss, treatment of infiltrated groundwater, water and wastewater treatment costs, pumping costs, maintenance expenditures (such as those incurred on flushing of pipes and minor repairs), and emergency expenditures (repair breaks and blockages, etc). Since operational costs increase with worsening pipe condition state, the $UnitPriceOpEx$ (the operational cost per unit length of a completely new pipe) is multiplied by the $ConditionMultiplierOpEx$. In the demonstration model the exponential $ConditionMultiplierOpEx$, shown in Figure 2.5, is implemented to increase operational expenditures with increases in the $Average\ Condition$ determined using Equation 2.3.

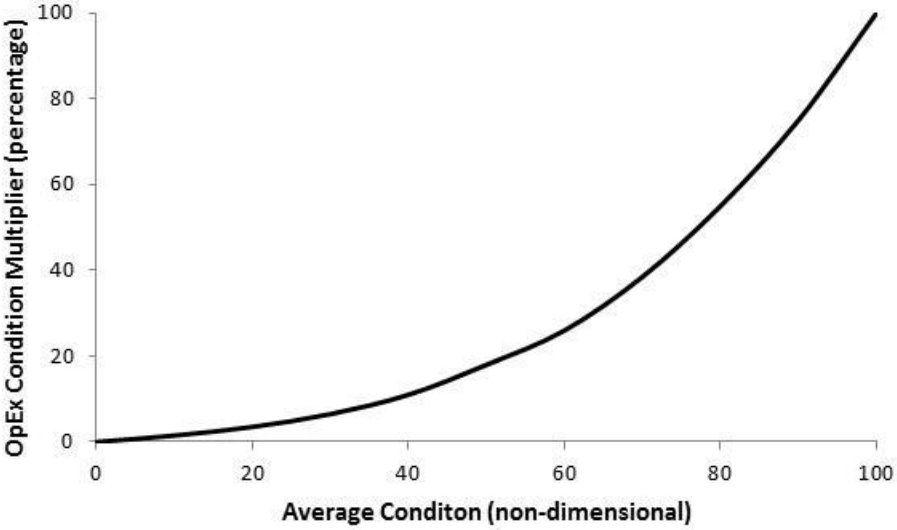


Figure 2.5: Condition Multiplier for operational expenditures.

Stock $UserFees$ tracks the price per unit volume of water charged to consumers. $UserFees$ are maintained at a constant level throughout a simulation or allowed to vary at each time step. A financially self-sustainable utility implies maintaining a "zero" $FundsBalance$. This means that revenues at each time step are equal to operational and capital expenditures. To set revenues equal to expenditures, stock $UserFees$ is adjusted using inflow $UserFeeHike$ and outflow $UserFeeDecline$.

Equations used to develop the demonstration model are presented in Appendix A.

2.5 Demonstration Model Simulations

2.5.1 Initial conditions and assumptions

Using the system dynamics model, described in Section 0, a number of simulations are preformed to explore the impact of the interconnections and feedback loops on a hypothetical water and wastewater utility. The hypothetical utility is assumed to maintain 700 kilometres of pipes which serve 100,000 consumers. This assumption is consistent with data reported in Burnside (2005). For this analysis, the pipe network length and customer base are considered constant over the simulation period. This assumption is deemed valid for the case where expansion of the pipe network is funded through development charges. Inflation is not considered in these simplified demonstrations. It is also assumed that the utility manager is only responsible for the water distribution and wastewater collection network. This analysis represents the scenario where the linear networks are owned and managed by a lower tier of municipal government and the water and wastewater treatment plants are managed by an upper tier government. In this case the upper tier government sells water and charges the lower water utility for treatment of discharged wastewater back to the upper tier. This case is applicable to several Canadian municipalities.

Table 2.1 provides the initial distribution of pipes in each condition group stock. All pipes are assumed to have an average service life of 100 years. The initial and minimum water demand are set at 300 and 200 litres per capita per day (lpcd) respectively, which are in accordance with data reported in Environment Canada (2006). Capital and operational expenditure unit prices are set at $1,000 and $50 per metre, respectively, which are in accordance with cost functions reported in Burnside (2005). These unit prices are assumed constant during the simulations. Thus, the rate of appreciation of costs (inflation rate) is equal to the project depreciation rate needed to discount all costs to present value. A user fee of $3.75 per m^3 is used to set initial revenues equal to expenditures.

Table 2.1: Initial distribution of pipes in various Condition Groups.

	Pipe Groups				
	Condition 20	**Condition 40**	**Condition 60**	**Condition 80**	**Condition 100**
Length (kilometers)	140	280	140	105	34
Fraction of Network (%)	20	40	20	15	5

Heare (2007) suggests that estimation of full long-term costs of water services requires a time horizon of a century or more. For this analysis, a 100 year simulation period is used. Table 2.2 provides a summary of the three scenarios with variations that are described in the introduction. The demonstration model is used to explore three scenarios with three annual rehabilitation strategies: (Scenario 1) no capital works expenditure to rehabilitate water and wastewater pipes within the network; (Scenario 2) a 1% annual rehabilitation strategy that will replace the entire network every

100 years, assuming the average age of the pipe is 100 years; and (Scenario 3) no more than 5% of the network with pipes in $Condition\ Group\ 100$, which implies an annual rehabilitation rate of 1.18% of the network. For each scenario (Case A) user fees are maintained at \$3.75 per m^3 or (Case B) allowed to change so that revenues equal expenditures at each time step or (Case C) allowed to change so that revenues equal expenditures but with price elasticity of demand for water.

Table 2.2: Summary of Simulation Scenarios

Scenario	**Rehabilitation Strategy (% of network replaced)**	**Zero Funds Balance Enforced**	**Price Elasticity of Demand (%/%)**
1A	0.00	No	0.00
1B	0.00	Yes	0.00
1C	0.00	Yes	-0.35
2A	1.00	No	0.00
2B	1.00	Yes	0.00
2C	1.00	Yes	-0.35
3A	1.18	No	0.00
3B	1.18	Yes	0.00
3C	1.18	Yes	-0.35

Boland et al. (1984) indicate that price elasticity for residential water demand varies between -0.2 to -0.5. For this study, price elasticity is set at -0.35. For the price elastic simulations, a 20-year water demand adjustment period is applied.

2.5.2 Simulation results

The zero percent rehabilitation strategy (1A, 1B and 1C) is a “do nothing” reactive maintenance management strategy where pipes are fixed at the time of failure. Scenario 1 simulation results are provided in Figure 2.6.

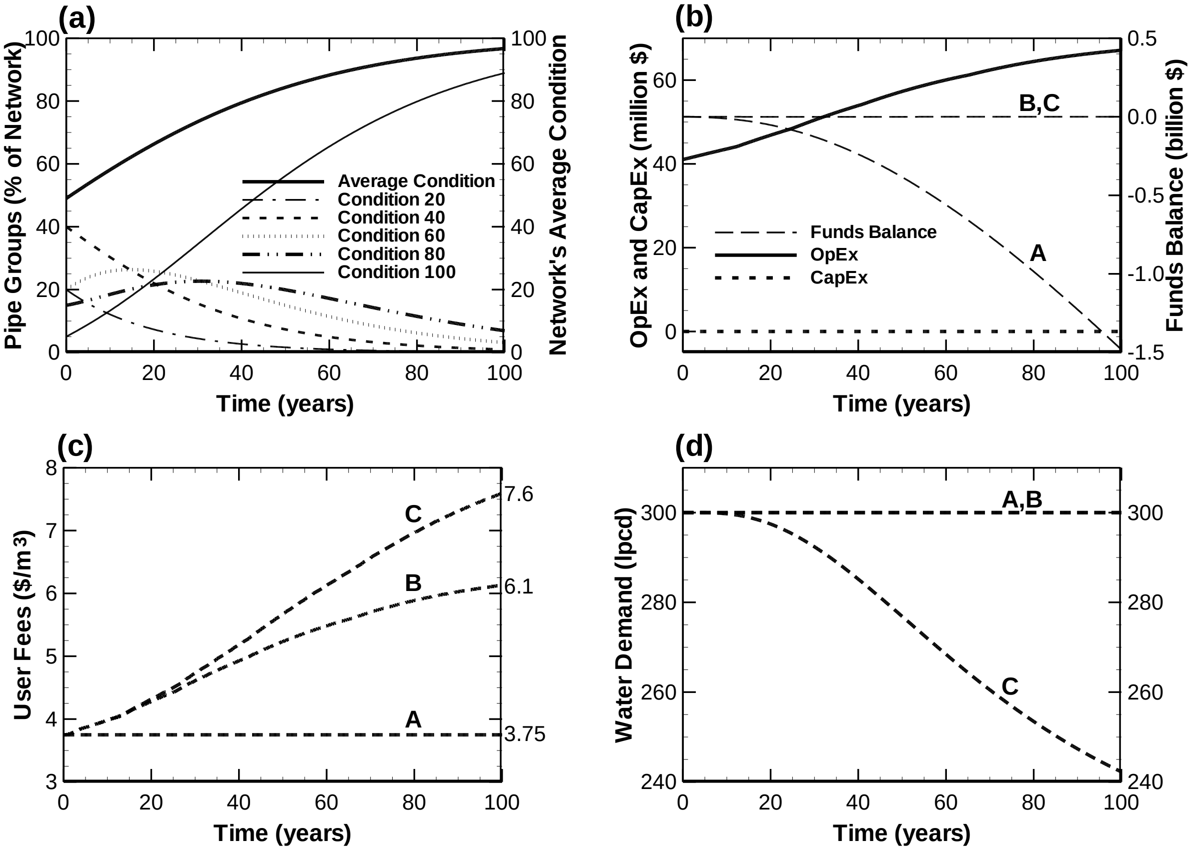


Figure 2.6: Simulation results for Scenarios 1.

Figure 2.6a shows the pipe network average condition along with the percentage of pipe network in each of the pipe condition stocks over a 100-year simulation period. This figure shows the network to have an initial average condition of 49 and that the average condition increases rapidly to 88 by year 60 and finally to 97 in year 100. Figure 2.6a shows that the percentage of pipes in stock $\mathit{Condition\ Group}\ 100$ increases rapidly from 5 to 89 percent in 100 years.

Figure 2.6b shows capital and operational expenditures along with the net funds balance over the 100-year simulation period. This figure shows the following:

- Capital work expenditures are nil over the entire simulation period. This is reasonable since no funds are invested to rehabilitate the pipes.
- Annual operational expenditures increase from \$42 to \$67 million. This is deemed reasonable as operational expenditures will increase with average network condition and the trend of the operational expenditures follows the average network condition curve in Figure 2.6a.
- Curve A in Figure 2.6b shows that the funds balance initially starts at zero and then decreases rapidly to -1.5 billion dollars at 100 years, while curves B and C show that the net fund balance remains constant at zero over the entire 100 year simulation period. This confirms that the implemented Zero Fund Balance routine works as designed. The zero fund balance is accomplished by adjusting the user fees so that revenue equals to expenses in each time step.

Figure 2.6c shows the per cubic metre user fees of water and water and wastewater services over the 100 year simulation period. Curve A shows that the unit price of water is constant at \$3.75 per m^3 in real dollar terms. Curves B and C show how the user fees changes to create a zero funds balance without and with price elasticity respectively. Both curves B and C show an increasing user fee with time. This increasing user fee is required to increase revenue in step with increasing operational expenditures that result from deteriorating infrastructure. Curves B and C follow the same trend up to approximately 15 years where Curve C shows a rapid increase in user fee compared to Curve B. By the year 100, a price elasticity of -0.35 requires a user fee of \$7.6 per m^3 to balance the funds while zero price elasticity requires a user fee of \$6.2 per m^3.

Figure 2.6d shows the water demand over the 100 year simulation period. This figure shows that the water demand is constant at 300 lcpd when price elasticity is not enforced (curves A and B). Curve C shows that enforcing price elasticity results in the water demand decreasing from 300 lcpd to 242 lcpd in year 100. It should be noted that the utility’s revenues are a function of water usage and reduced water consumption reduces revenues. To maintain a zero fund balance (revenues = expenses) a higher user fee is required with price elasticity. The higher user fee (\$7.6 vs \$6.2 per m^3) with price elasticity enforced is deemed reasonable.

Figure 2.7 and Figure 2.8 show simulation results when proactive annual pipe network rehabilitation strategies are used. Specifically, Figure 2.7 presents results for Scenario 2 which involves a 1% annual rehabilitation rate, and represents 100 percent pipe replacement in 100 years. Figure 2.8 presents results for Scenario 3 where the annual rehabilitation rate is increased to 1.18% so that no more than 5% of the network has pipes in $Condition\ Group$ 100 for the entire 100 year simulation period. For the proactive pipe rehabilitation scenarios (Scenarios 2 and 3), pipes in stock $Condition\ Group\ 100$ are rehabilitated in accordance with the rehabilitation criteria (i.e. 1.0% or 1.18%). In all simulations the length of pipe rehabilitated is set to the maximum of the length set by the rehabilitation strategy or the length of pipes in stock $Condition\ Group\ 100$.

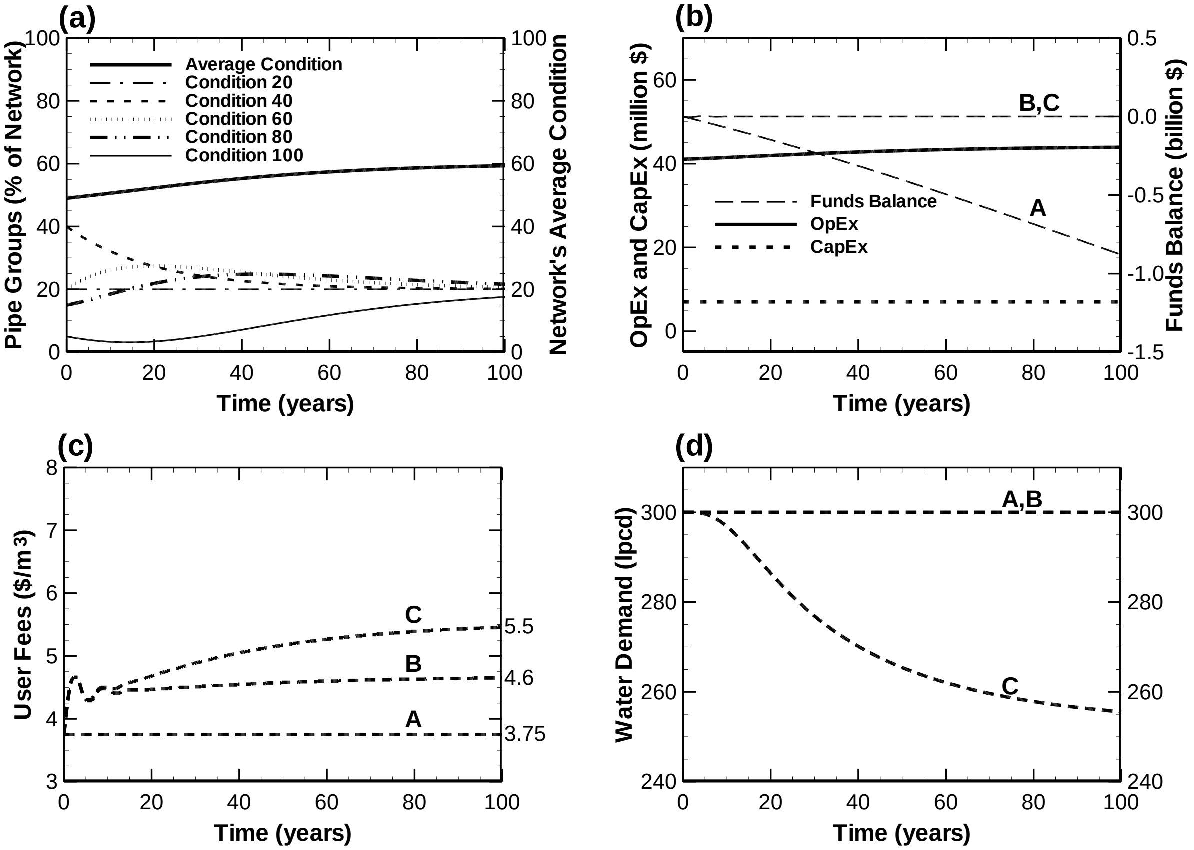


Figure 2.7: Simulation results for Scenarios 2.

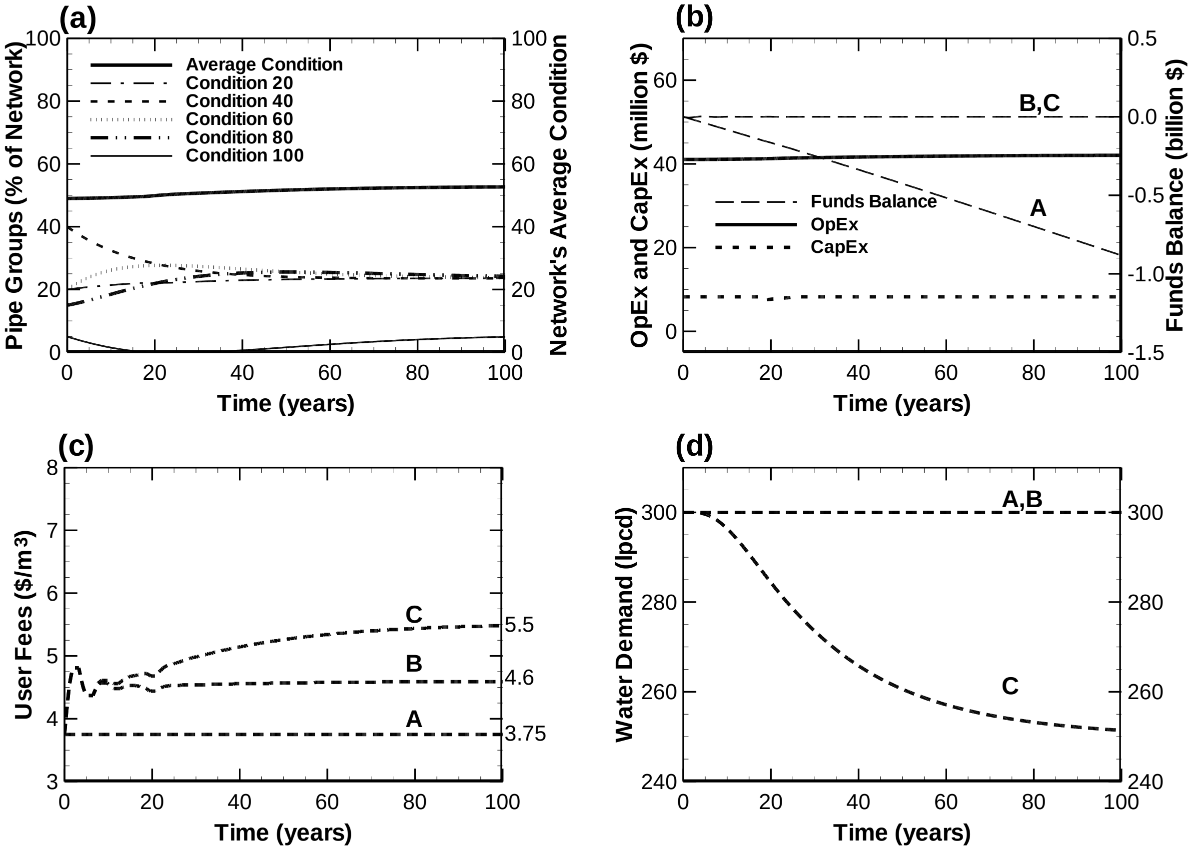


Figure 2.8: Simulation results for Scenarios 3.

Figure 2.7a shows the average network condition increases from 49 to 59 in 100 years. Figure 2.8a shows the average network condition starts at 49 and slowly increases to 53 by the end of the simulation. It should be noted that the no rehabilitation strategy resulted in an average network pipe condition of 97 at year 100. Figure 2.7a shows 5 percent of the network in stock $Conditon\ Group\ 100$ at year 0 decreases to 3% at year 15 then increases to 18% at year 100. Figure 2.8a shows stock $Conditon\ Group\ 100$ decreases to 0% at year 15, remains constant at 0% until year 37 then increases linearly to 5% at year 100. An increasing stock $Conditon\ Group\ 100$ indicates that more pipe lengths are arriving into the stock than rehabilitated and a decreasing stock trend indicates that more pipes are rehabilitated than arriving into the stock. For the no rehabilitation option the percentage of network in stock $Conditon\ Group\ 100$ increases rapidly to 89% in 100 years.

Figure 2.7b and Figure 2.8b show that the fund balance is zero over the 100 year simulation period when the Zero Fund Balance routine is implemented (curves B and C). When the user fee is maintained at \$3.75 per m^3, the funds balance decreases to -\$0.9billion when the rehabilitation is set at 1.0% and 1.18%. These funds balance deficits are significantly less than the -\$1.5 billion for the no rehabilitation strategy. Figure 2.7b shows that the annual operational expenditures increase linearly from \$41 to \$44 million in year 100 while Figure 2.8b shows the annual operational expenditures increase from \$41 to \$42 million in 100 years. Final year operational expenditures of \$44 and \$42 million are significantly less than the \$66 million required for the no rehabilitation strategy. Figure 2.7b and Figure 2.8b show annual capital expenditures for the 1.0% and 1.18% rehabilitation options are \$7.0 and \$8.3 million respectively. For the no rehabilitation option the capital expenditure costs are \$0 annually.

Figure 2.7c and Figure 2.8c shows changes in annual user fees over the simulation period for the 1.0% and 1.18% rehabilitation scenarios operated on a financially self-sustaining basis (zero funds balance). The impact of price elasticity is shown in curves B and C. For both rehabilitation strategies, the user fee generally increases linearly to \$4.6 per m^3 when no price elasticity is considered and increases with a decreasing slope to \$5.5 per m^3 when price elasticity is considered.

Figure 2.7d and Figure 2.8d show that water demand is constant at 300 lpcd when no price elasticity is considered (curves A and B) and initially rapidly decreases then levels off when price elasticity is considered. Final water demand for the 1.0% and 1.18% scenarios is 257 and 252 lpcd respectively. These values are higher than the 242 lpcd water demand for the no rehabilitation strategy (curve C in Figure 2.6d).

2.6 Discussion

Table 2.3 provides a summary of all simulation results at year 100. Regulations in Canada are forcing utilities to be financially sustainable and similar pressures are likely to occur or have occurred in other developed countries. Case 1A shows that a constant user fee of \$3.75 per m^3 with no annual rehabilitation strategy will result in the utility having a deficit of \$1.5 billion at year 100. To make the utility financially sustainable, user fees need to be increased to \$6.13 per m^3 by year 100 (65% increase). When price elasticity is considered, users fees need to be increased to \$7.59 per m^3 by year 100 (102% increase). When a proactive annual pipeline rehabilitation strategy of 1.0% is adopted (Case 2B), a self-sustainable user fee of \$4.65 per m^3 is required at year 100. This represents a 24% increase in user fees. If price elasticity is considered (Case 2C), a user fee of \$5.46 per m^3 is required at year 100. This represents an increase of 46%. When the annual rehabilitation strategy is 1.18%, the simulation results for user fees are similar to the 1.0% rehabilitation cases.

Table 2.3: Summary of results at year 100.

Scenario	**Final User Fee ($/m^3)**	**Funds Balance (billion$)**	**Final Water Demand (lpcd)**	**Cumulative Operational Expenditures (billion $)**	**Cumulative Capital Expenditures (billion $)**	**Cumulative Total Expenditures (billion $)**	**Network Average Condition**
1A	3.75	-1.48	300	5.57	0.00	5.57	97
1B	6.13	0.00	300	5.57	0.00	5.57	97
1C	7.59	0.00	242	5.57	0.00	5.57	97
2A	3.75	-0.88	300	4.29	0.70	4.99	59
2B	4.65	0.00	300	4.29	0.70	4.99	59
2C	5.46	0.00	256	4.29	0.70	4.99	59
3A	3.75	-0.88	300	4.17	0.82	4.99	53
3B	4.59	0.00	300	4.17	0.82	4.99	53
3C	5.48	0.00	251	4.17	0.82	4.99	53

For the no rehabilitation strategy the total expenditure over 100 years is $5.57 billion. When 1.0% or 1.18% annual rehabilitation is adopted, the total expenditure over 100 years is $4.99 billion. This represents a $0.58 billion (10%) saving with significantly lower user fees at year 100.

It is worth noting that cumulative expenditures at the end of the simulation are the same for the 1.0% and 1.18% rehabilitation strategies even though annual capital and operational expenditures are different. This is due to maintaining the network in a better condition state which reduces operational costs.

When price elasticity is included, an increase in user fees causes water consumption to decrease (curve C representing elastic water demand in Figure 2.6d, Figure 2.7d and Figure 2.8d). Reduced volume of water billed to customers yields lesser revenues than required to match expenditures. Hence, funds balance decreases and user fees need to be increased. Due to the influence of loop R2 (Section 2.2.3), curve C (variable user fee with elastic demand) in Figure 2.6c, Figure 2.7c and Figure 2.8c moves away from curve B (variable user fee with inelastic demand). This widening of gap between curves B and C continues for the case of no rehabilitation (Figure 2.6c). However, in cases with proactive rehabilitation, the departure of curve C from curve B decreases and finally stops (slope of curve C in Figure 2.7c and Figure 2.8c decreases to finally become zero). This slowing trend of departure is due to feedback loop R3 (Section 2.2.6). This loop is not operative for scenario 1 because for that scenario, one of variables along loop R3 i.e. Infrastructure Rehabilitated remains zero. For scenarios 2 and 3, however, Infrastructure Rehabilitated continuously increases. As a result, infrastructure condition decreases (improves) which in turn causes operational expenditures to decrease. With reduced operational expenditures fund balance increases. Since fund balance is an element common to both loops R2 and R3, the influence of loop R2 is mitigated by loop R3.

The above discussion highlights the influence of two feedback loops (R2 and R3) on water and wastewater network management. Thus, this study demonstrates the complexity of the system. To model a complete system, more feedback loops need to be added to the model. For example in the demonstration model, to achieve zero fund balance, user fees were adjusted without any constraints. However, it may not be politically possible to implement large user fee hikes instantaneously. Thus, feedback loop B2 needs to be included in a more complete model. Once it is recognized that user fees may not always be at desired levels, it then follows that the constraint of funds available for infrastructure rehabilitation must be included. Thus, inclusion of loop B2 would necessitate capturing the influence of feedback loop B3. Similarly, another simplifying assumption in the demonstration model is to aggregate water and wastewater pipes. In a complete model, pipes can be classified according to criteria such as material, age and diameter. With such additional details, it is possible to incorporate deterioration curves to model movement of pipes among various stocks (Section 2.4.1). Accordingly, feedback loop R1 needs to be included.

Finally, there may be other important feedback loops in addition to the ones discussed in Section 2.2 that are required to capture the complex and dynamic behaviour of water and wastewater network management. For example, Canadian municipalities are allowed to borrow for financing capital projects. Such a financing mechanism involves additional feedback loops to be considered. Once a complete model is validated and calibrated, it can be used to develop strategic plans to ensure water utilities are financially self-sustainable over the long-term.

2.7 Conclusions

The following conclusions are drawn from this study:

1. New regulations in Canada mandate that water utilities are managed such that they are financially self-sustainable over the long-term.
2. Existing infrastructure management systems and tools reported in the literature are not capable of helping Canadian municipalities meet the requirements of the new regulations.

3. A causal loop diagram is developed that demonstrates water and wastewater network management is a complex system with many interconnections and feedback loops. This is the first known causal loop diagram developed for a financially self-sustainable water utility.
4. The system dynamics approach is deemed an acceptable modelling method for water and wastewater network management.
5. A demonstration system dynamics model is developed that highlights the significance of interconnections and feedback loops. This is the first known application of system dynamics to water and wastewater network management.

A complete system dynamics model needs to be constructed, validated and calibrated for a water utility before it is used to determine financial sustainability.

Chapter 3

Financially sustainable management strategies for urban wastewater collection infrastructure: development of a system dynamics model

3.1 Introduction

A large majority (80%) of Canadians live in cities (Statistics Canada, 2006). The economic prosperity and quality of life in these communities is supported by physical infrastructure such as highways and roads; bridges and overpasses; water and wastewater systems; and other facilities (Harchaoui et al., 2004; Brox, 2008). Among these vital infrastructure assets, water distribution and wastewater collection networks can be called the 'life-lines' of cities because these are used for safe and reliable delivery of clean drinking water and disposal of wastewater. In Canada, a majority of these networks are owned and operated by municipal governments. Due to their limited financial resources, municipal governments have found it difficult to adequately invest in the preservation and rehabilitation of all their physical infrastructure assets (Mirza, 2007). Water and wastewater networks have especially suffered in this respect because they are hidden underground and have therefore attracted limited attention compared to the more visible assets (Brubaker, 2011). The deferred investments needed to repair and prevent deterioration of existing infrastructure assets have been accumulating rapidly. Mirza (2007) refers to this accumulated deferred investment as an infrastructure deficit. He reports that for water and wastewater systems, infrastructure deficit grew from $21 billion to $31 billion over the period from 1996 to 2007. Moreover, this deficit is in addition to the new needs of $56.6 billion for these systems (Mirza, 2007).

As a result of neglect and inadequate investments, water and wastewater systems have continued to deteriorate, posing a threat to public health and the environment (Brubaker, 2011). This became tragically evident in the case of Walkerton, Ontario where seven people lost their lives and thousands more became sick due to contamination of the municipal water drinking supply system (Brubaker, 2011). To protect human health, the Province of Ontario enacted the Safe Drinking Water Act 2002 as recommended by the Walkerton Inquiry Commission (Ministry of the Environment, 2002). Among the several regulations made under the authority of this legislation, Regulation 453/07 deals with financial plans for municipal water systems. This regulation requires that all public water utilities prepare and publish long-term financial plans. Municipal councils are now required to attest to the financial sustainability of water and wastewater systems (Ministry of the Environment, 2007a). A key principle underlying the financial sustainability requirement is that revenues are sufficient to pay all expenses of providing services (Ministry of the Environment, 2007b). Besides the provincial regulations, public water utilities have to comply with new reporting requirements as enunciated in the Public Sector Accounting Board (PSAB) statement PS3150. Specifically PS 3150 requires that all local governments in Canada, starting in January 2009, report all tangible capital assets along with their depreciation on financial statements (CICA, 2007). It is anticipated that with the new reporting standards decision makers will become aware of the full cost of services and thus make informed decisions regarding maintenance, renewal, replacement, financing, and rate-setting issues (CICA, 2007).

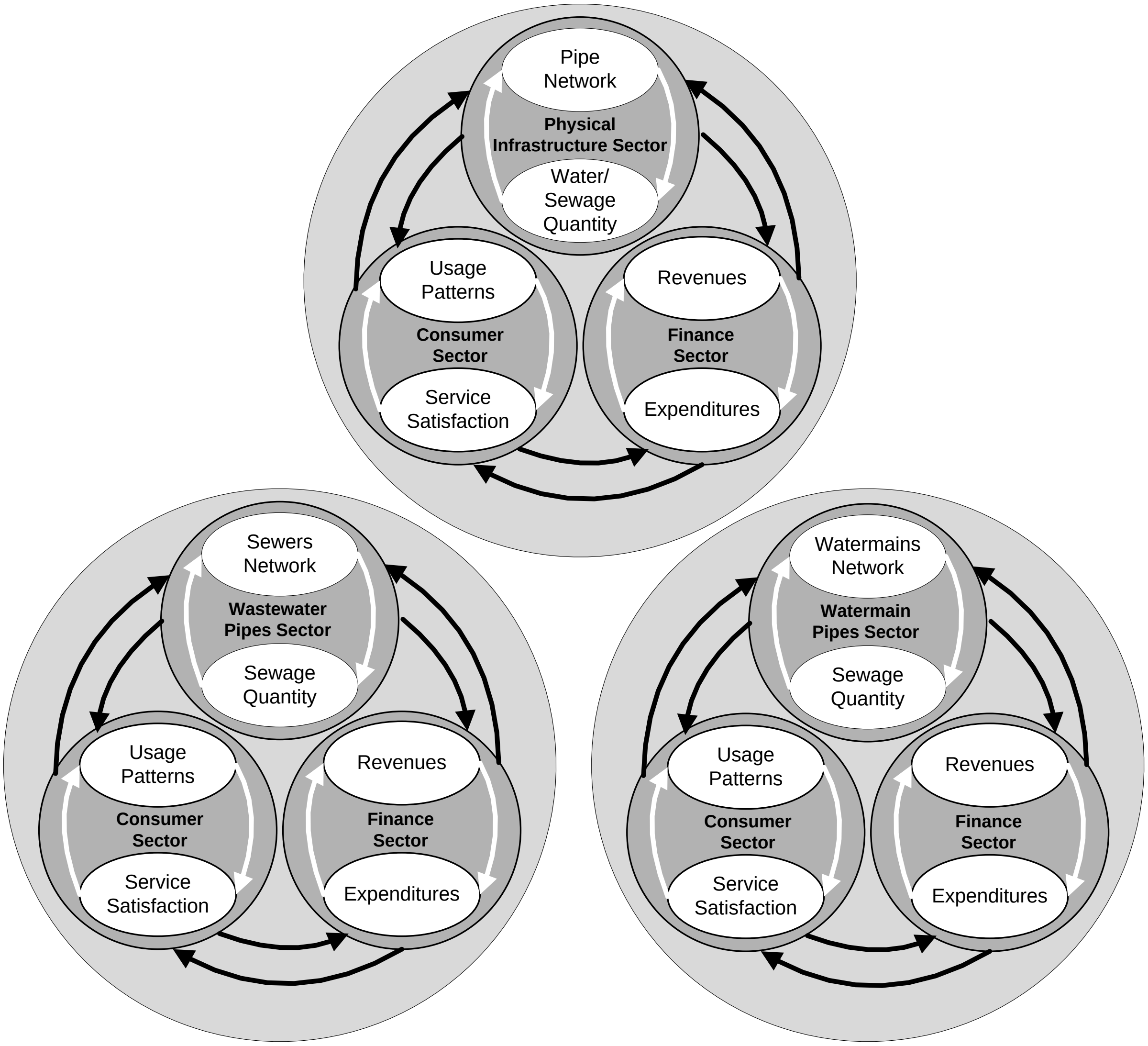
The major reason for financial sustainability based on full-cost recovery is to achieve economic efficiency (McNeill and Tate, 1991; Harris et al., 2002). Historically, Canadian water utilities have relied on grants from senior levels of government and supported by general sources of municipal income such as property taxes. User fees accounted for only 37 percent and 66 percent of their operational and capital expenditures respectively (Renzetti, 1999). Moreover, user fees were typically designed to recover operational expenditures and did not account for depreciation of capital assets. User fees that are subsidized through grants and do not fully reflect the cost of providing services are economically inefficient. This inefficiency means that public money is misallocated in that excess capacity is installed and overconsumption is encouraged (Renzetti, 1999; Swain et al., 2005). The new regulations seek to redress these issues by not allowing financial plans to be based on external sources of revenue (Regulation 453/07) and requiring explicit accounting for depreciation of capital assets (PS 3150).

It must, however, be noted that water and wastewater services are deemed public goods because of their public health and environmental externalities (Harris et al., 2002). This implies that decision makers have to also consider affordability while setting user fees for these services.

Thus, the challenges faced by water and wastewater utility managers include rejuvenating existing infrastructure assets while meeting demands of new growth; maintaining acceptable levels of service; complying with financial self-sustainability and other regulatory requirements; and, gaining the support of various stakeholders for their management policies. The situation is further compounded by the fact that these issues are inherently interrelated and cannot be addressed in isolation to each other (Ginley and Ralston, 2010). Such interrelationships for a water and wastewater utility are identified in Chapter 2 using the formal method of causal loop diagram. In Chapter 2 it is shown that these interrelationships give rise to feedback loops which are in turn responsible for complex dynamic behaviour. A demonstration system dynamics (SD) model is also presented to quantify the impact of feedback loops on management strategies of water and wastewater networks. The conceptual framework employed in Chapter 2 is illustrated in Figure 3.1a. This framework is a high level representation of water and wastewater network management and consists of physical infrastructure, finance, and consumer sectors. Within the physical infrastructure sector, water and wastewater pipes are aggregated together. The causal loop diagram developed for this framework illustrates only a few of several interacting feedback loops. Furthermore, financial sustainability is modelled as maintaining a zero fund balance only with no allowance for debt financing of capital projects or building up cash reserves.

To overcome the limitations of the framework presented in Chapter 2, it is necessary that the physical infrastructure sector (Figure 3.1a) is disaggregated into wastewater and watermain pipes sectors. Two conceptual frameworks are thus created, one for wastewater collection networks and another for watermain distribution networks. This chapter focuses on the conceptual framework for management of wastewater collection network as shown in Figure 3.1b. Management of water distribution networks (Figure 3.1c) is addressed later in Chapter 5.

(a): Conceptual framework of water and wastewater network management presented in Chapter 2



(b): Conceptual framework of wastewater collection network management presented in Chapter 3

(c): Conceptual framework of watermain distribution network management presented in Chapter 5

Figure 3.1: Conceptual frameworks for modelling financially self-sustaining water and wastewater networks.

Specific objectives of this research include development of a causal loop diagram (CLD) and a system dynamics model, for management of municipal wastewater collection networks under the paradigm of financial self-sustainability. The CLD is a unique contribution of this study that seeks to identify pertinent interconnections among the physical, financial, and social components of the system. More importantly, the developed CLD should help identify feedback loops that exist due to such interconnections. The system dynamics model is the first known decision support tool for financially sustainable management of wastewater collection networks that takes into account interconnections and feedback loops among system components. The model is essentially a mathematical representation of the CLD. It attempts to capture cost drivers and revenues sources in the system and includes a set of policy levers which allow formulation of various financing and rehabilitation strategies. Alternative strategies can be compared using a variety of performance indicators provided in the model.

It is hoped that the causal loop diagram serves as a useful qualitative tool for developing an appreciation of interrelationships and feedback loops and thus leads to a better understanding of the system behaviour. The system dynamics model is presented as a decision support tool that should help municipal water utilities devise strategic plans which fulfill regulatory obligations and meet customer expectations regarding cost and quality of services.

The following section provides a brief overview of existing literature relevant to management of wastewater collection networks. Section 3.3 delineates scope of this study. A causal loop diagram for the system is presented in Section 3.4. The system dynamics model is developed in Section 3.5 and its data requirements are discussed in Section 3.6. Conclusions drawn from the research are listed in Section 3.7.

3.2 Literature Review

Decision support tools have been developed to aid utility managers in maintaining water and wastewater infrastructure assets at acceptable levels of service while reducing costs associated with provision of services. These tools include some or a combination of these functionalities: collection and registration of data related to infrastructure components; assessment and grading of the asset conditions; analysis of data for predicting remaining service life; comparison of costs of repair/rehabilitation alternatives over their life cycles; and, prioritization of rehabilitation activities that ensure maximum benefits at minimum costs (Grigg, 2003). A brief survey of decision support tools applicable to wastewater collection networks is provided below.

Wastewater pipes are inspected using closed circuit television and zoom camera systems, sewer scanner evaluation technology, laser profilers, non-destructive and remote-sensing techniques, and multi-sensory systems (Wirahadikusumah et al., 1998; Costello et al., 2007; Rizzo, 2010). Recognizing the importance of managing the collected data, Halfawy and Figueroa (2006) present a GIS-based asset data repository for municipal infrastructure. Younis (2010) points out the heterogeneity of data from multiple sources and formats at different utilities. He offers a solution to this by presenting a framework for data integration using extensible markup language (XML) specifications and technologies.

Various condition rating protocols are available for wastewater pipes. Most Canadian municipalities either directly employ the protocol published by the Water Research Centre (WRc) in United Kingdom or use it as a basis for their own customized protocols (Rahman and Vanier, 2004). According to the WRc protocol (WRc, 2001), pipes are assigned internal condition grades (ICG) on a scale of 1 to 5 based on their structural and operational defect scores. Internal condition grade 1 represents the best condition while ICG 5 represents the worst or collapsed state. Defect scores for pipes are usually assessed manually but efforts are being made to automate this process (Sarshar et al., 2008).

Baur and Herz (2002) use a cohort survival model to determine residual life expectancies of sewer pipes. The procedure involves organizing pipes into ‘cohorts’ sharing common characteristics such as material, diameter, and period of construction. Historic condition data of sewer pipes is used by Najafi and Kulandaivel (2005) to train an artificial neural network model for predicting future condition states. Baik et al. (2006) propose a Markov chain-based deterioration model for which transition probabilities of different condition states are estimated using an ordered probit model. Savic et al. (2006) use evolutionary polynomial regression to develop models for predicting wastewater blockage events and collapse failures. Continuation ratio and cumulative logit models are employed by Younis and Knight (2010a; 2010b) to determine wastewater pipes’ service life based on pipe age, material and internal condition grades. A state-of-the-art review of sewer deterioration modelling research is provided by Ana and Bauwens (2010).

deMonsabert et al. (1999) use an integer program to optimize the rehabilitation schedule of a sewer system while considering costs of rehabilitation and treatment of inflow and infiltration flows.

Ariaratnam and MacLeod (2002) use linear programming to prioritize sewer pipes for inspection and repairs under annual budgetary constraints. Wirahadikusumah and Abraham (2003) apply probabilistic dynamic programming in conjunction with a Markov chain model to analyze life-cycle costs of combined sewer systems. Saegrov (2006) presents CARE-S, a comprehensive decision support system that combines several tools relevant to wastewater infrastructure management into a single platform. These tools allow for: assessment and forecast of performance indicators, socio-economic and environmental risk definition, assessment and prediction of structural, hydraulic and environmental conditions of sewer networks, and optimization of rehabilitation investments. Arthur and Crow (2007) develop a methodology that prioritizes capital maintenance expenditures for sewer pipes on the basis of customer serviceability criteria.

Halfawy et al. (2006) reviewed the following commercial municipal asset management systems: Synergen, CityWorks, MIMS, Hansen, RIVA, Infrastructure 2000, and Harfan. They found the majority of existing commercial asset management software to focus on operational management (e.g., work orders, service requests) with little or no functionality to support long-term renewal planning decisions (e.g., deterioration modelling, risk assessment, life cycle cost analysis, asset prioritization). From the reviewed systems, RIVA, Harfan, and Infrastructure2000 implemented some level of support for long-term renewal planning of specific assets, mainly pavement. The other four systems included condition assessment and rating modules. Most of these commercial software tools now incorporate PSAB and other legislation annual reporting requirements and have improved strategic long range asset, risk and budget management by forecasting the full lifecycle of infrastructure assets. They also generate a lifecycle cost and risk profile for each asset, determine the events that should be scheduled for each period, as well as, the impact on cost, condition, risk and capacity. None of these tools are water and wastewater asset specific management tools.

The above survey indicates that significant progress has been made in development of decision support tools for management of wastewater collection networks. However, it also reveals that currently no decision support tool exists that considers the impact of feedback loops and interconnections between wastewater collection network, finance and social sectors. Another thematic area in the literature does address the issue of such complex interactions. Although not specifically focussed on management of wastewater collection networks, this research strand is explored below because of its relevance to the current study.

Grigg and Bryson (1975) present a simulation model that is comprised of four interconnected sectors – financial accounting, water balance, water use, and population growth. Guest et al. (2010) study interactions among sustainability aspects related to decentralized wastewater treatment systems using a qualitative system dynamics approach. Ahmad and Prashar (2010) also use a system dynamics model to study interconnections among population growth, land use changes, water demand, and water availability. Adeniran and Bamiro (2010) model the interconnections among Finance, Production, Distribution, and Operation & Maintenance sectors of a municipal water supply system. However, they exclude the water and wastewater network within their proposed municipal water supply system. Bianchi and Montemaggiore (2008) point to the dynamic complexity of public utility management and as a solution propose integration of the balanced scorecard approach with a system dynamics methodology. Accordingly, they present a model for strategic management of a municipal water company that includes a distribution sector, sewer sector, human resources sector and financial sector. The sewer sector deals with wastewater treatment capacity but does not address maintenance or rehabilitation of the wastewater network.

Thus, the literature review reveals two thematic strands of research. One is primarily focussed on the engineering and financial aspects of managing wastewater collection networks, while the other emphasizes the importance of interrelationships and feedback loops. An appreciation of such interconnections, especially within the context of financial sustainability, is found missing from the former research strand. The latter research strand includes studies of municipal water systems but has not been applied to management of wastewater collection networks.

3.3 Scope and Limitations of Study

This section first presents a brief discussion of expenditures and revenues for a typical water utility in the Province of Ontario. This information is then used to explain assumptions made in this study about the finances of the utility. Finally, other limitations of the study are specified.

Figure 3.2 provides a schematic overview of the cash flows for the utility. This figure shows that the utility's fund balance is determined by its annual expenditures and annual revenues. The annual total expenditures are broadly classified into capital expenditures ($CapEx$) and operational expenditures ($OpEx$). $CapEx$ is incurred on installation of new and major rehabilitation of existing pipes. $OpEx$ is the sum of sewage treatment, maintenance, and interest expenditures. Sewage treatment expenditures are incurred on treatment and disposal of annual sewage flow volumes including inflow and infiltration (I&I) flow volumes. Maintenance expenditures include costs such as salaries, office supplies, equipment, routine maintenance (pipe flushing and root removal) and emergency (unplanned) repairs of collapsed sewers. Interest expenditures are accrued on the utility's outstanding debt.

A utility's income is typically derived from three sources: development charges, user fee based revenue, and interest earnings. The utility receives one-time development charges from developers to extend wastewater services to new sub-divisions. Fee based revenue is the major and regular source of income which is collected from customers by charging sewage fee on their consumed (metered) volume of water. Another source of income can be interest earnings that are accrued on utility's cash reserves.

With the above definitions the scope of this study is laid out as follows. It is assumed that the utility's income does not include grants received from senior (provincial and federal) levels of government. This is partly motivated by the fact that such transfers have been largely discontinued (Brubaker, 2011). More importantly, Ontario Regulation 453/07 (Section 3.1) does not allow a utility's financial plans to be based on expectations of receiving grants (Ministry of the Environment, 2007a).

Development charges are assumed to be just sufficient to pay for capital expenditures of new construction. Thus, development charges are not used for any other expenditure categories nor are capital expenditures of new construction financed by other sources of income. This means that capital expenditures on new construction and development charges do not impact calculation of user fees.

It should be noted that financial self-sustainability requires that only revenues collected from provision of water and wastewater services should be used to meet the needs of providing these services (Ministry of the Environment, 2007b). Hence financing these services through other sources such as property taxes is not authorized. However, self-sustainability does not preclude using debt as a source of financing capital expenditure as long as the debt plus the associated interest expenditures are ultimately repaid using the utility's own revenues.

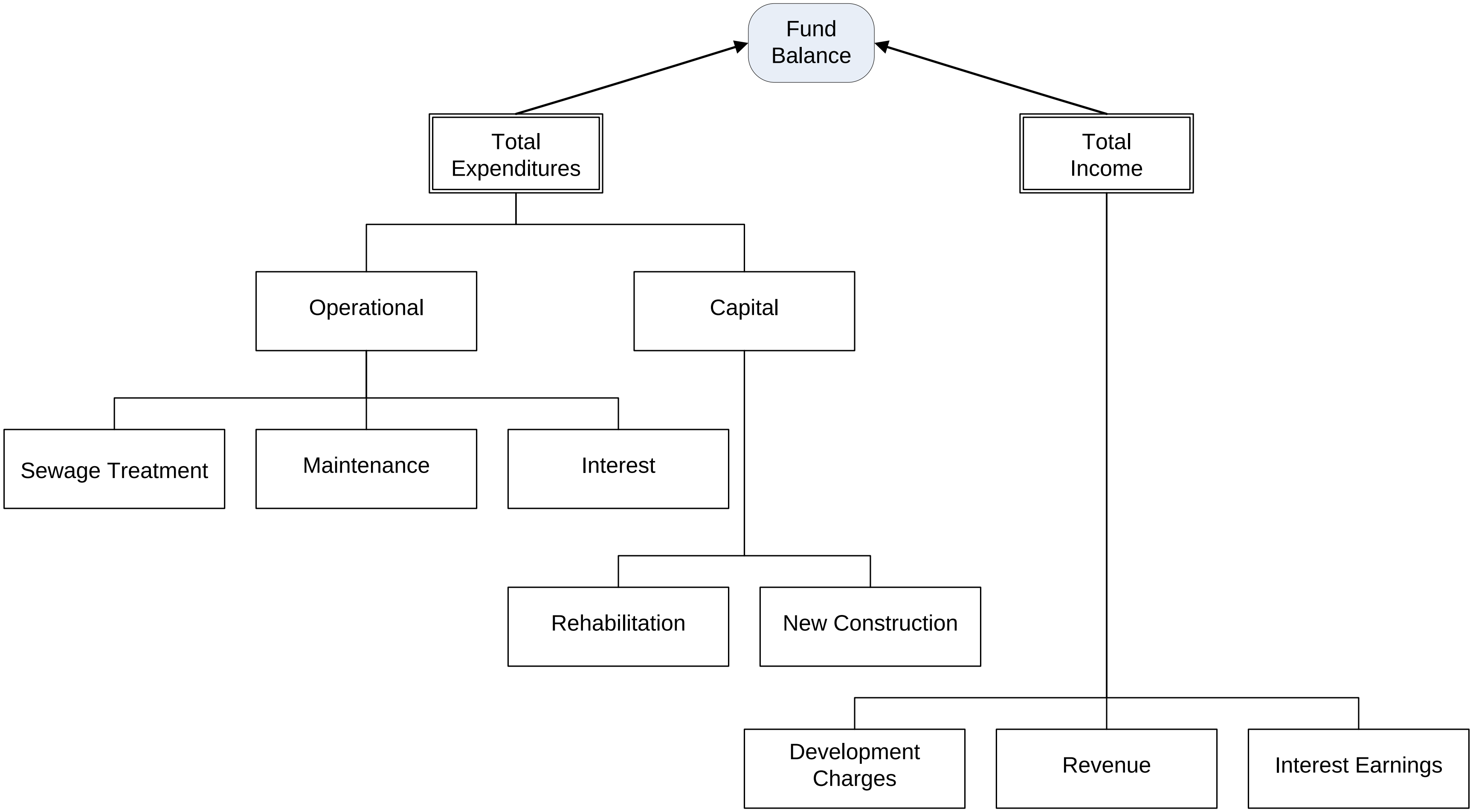


Figure 3.2: Expenditure and revenue categories for wastewater collection system

In addition to the above mentioned assumptions about finances of the utility, the following section describes the study's limitations in terms of scope.

Urban wastewater systems are comprised of various physical infrastructure assets such as laterals, wastewater pipes, maintenance holes, pumping stations, force mains, trunk sewers, and wastewater treatment plants. For this study only wastewater pipes are considered as these constitute 75%-88% of the life-time costs of wastewater systems (Burnside, 2005; Ashley and Cashman, 2006). In future work other physical assets will be included in the model. Thus, the proposed methodology for wastewater pipes (Section 3.5.1) is deemed to be applicable for all physical assets.

Although wastewater treatment plants are not explicitly modelled in this study, the costs associated with sewage treatment form part of the utility's operational expenditures (Figure 3.2). Thus, the developed model is deemed to be representative of Canadian municipalities with two-tiered local government in place (Kitchen, 2002). In such local governance, the upper tier municipality owns and operates wastewater treatment plant and charges the lower tier for treatment of sewage. The lower tier municipality owns and operates the wastewater collection network and collects fees from customers for the provision of wastewater services. Thus, the cost of sewage treatment is ultimately passed on to the customers as noted.

Storm sewer networks do not form part of this study because their financing mechanism is different than that of wastewater collection networks.

3.4 Causal Loop Diagram for Wastewater Collection Network Management

A causal loop diagram (CLD) is a formal tool used to graphically illustrate causal relationships among variables of a system. The CLD can be used to identify feedback loops that exist within the system under consideration. A feedback loop has causal relationships among system components such that when one component is changed, the perturbation traverses along the loop resulting in a change to the originating component (Hannon and Ruth, 1994). When a change in the originating component causes a change in other components that strengthens the original process, the feedback loop is termed a positive or a self-reinforcing loop. If the response of other components along the loop counteracts the original change, a negative or balancing loop is deemed to exist (Hannon and Ruth, 1994). When a system has multiple interacting feedback loops, then it is expected to exhibit complex dynamic behaviour (Sterman, 2000).

In a CLD, relationships between variables are depicted using arrows with a positive (+) or negative (-) sign placed besides the arrow head to indicate link polarity. A positive link polarity implies that "*if* *a cause increases, the effect increases above what it would otherwise have been*" and vice versa (Sterman, 2000). Similarly, a negative link polarity "*means that if the cause increases, the effect decreases below what it would otherwise have been*" and vice versa (Sterman, 2000).

A CLD for management of wastewater collection networks is presented in the following sections. It should be noted that the CLD is presented in three separate parts (Figures 3.3, 3.4 and 3.5). Causal links in these figures are shown using two types of arrows. The ones shown as solid lines imply that such causal links are implemented later in the system dynamics model (Section 3.5). While those shown as dashed lines are included for completeness of the CLD but are not implemented in the system dynamics model because these are beyond the scope of this work.

3.4.1 Feedback loops involving the wastewater network

Figure 3.3 shows feedback loops related to the physical condition of a wastewater collection network. In this figure, the deterioration process of pipes is represented by reinforcing loop $\mathbf{R_1}$. The rate of deterioration of a pipe is defined in terms of its existing condition. Using a numerical scale for internal condition grade (ICG) such as defined by WRc (2001), when the internal condition grade of a pipe increases then it will cause an increase in the pipe's deterioration rate. Increased deterioration rate implies that the internal condition grade of the pipe will increase even further. Thus, it takes lesser time for a pipe to deteriorate from ICG 2 to ICG 3, than it takes to deteriorate from ICG 1 to ICG 2. The same applies for the successive condition grades. Wirahadikusumah and Abraham (2003) report a similar exponential deterioration trend for sewer pipes.

Reinforcing loop $\mathbf{R_1}$ can be counteracted by the balancing loop $\mathbf{B_1}$. It can be assumed that in a functional society, a utility cannot choose to continuously ignore the deteriorating condition of its network. Regulatory mandates such as the service performance targets in the United Kingdom (Minister of State, 2008) and/or mounting customer dissatisfaction will force even an otherwise complacent utility to rehabilitate the network. Thus, loop $\mathbf{B_1}$ shows that an increase in the network condition grade will cause the utility to increase rehabilitation rate so that network condition grade is improved.

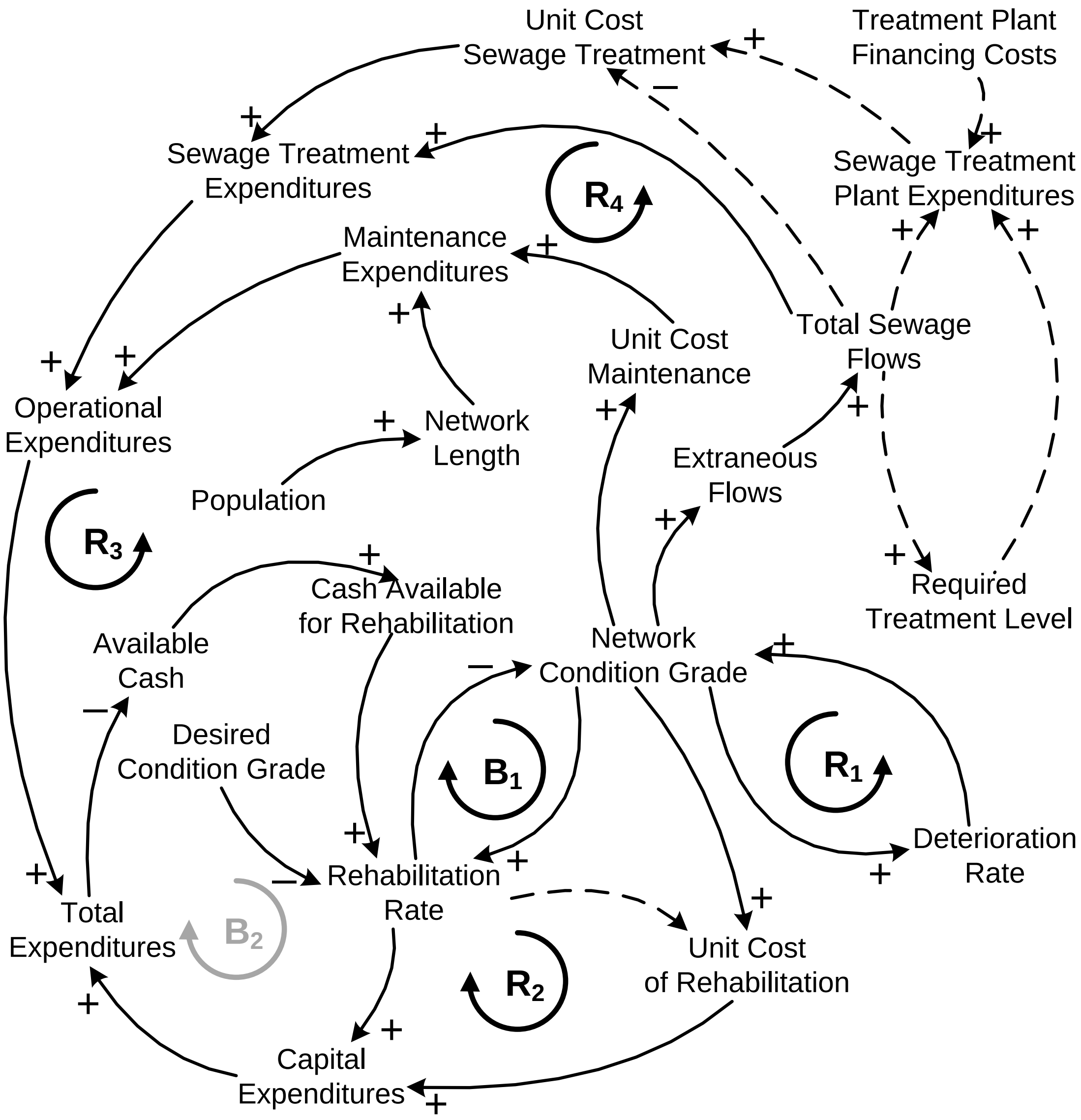


Figure 3.3: Feedback loops involving physical condition of wastewater collection network.

Reinforcing loop, $\mathbf{R_2}$, is formed due to connections among network condition grade, unit cost of rehabilitation, capital expenditures, total expenditures, available cash, cash available for rehabilitation, and rehabilitation rate. The cost of rehabilitating a unit length of pipe increases as a pipe moves from ICG 1 to 5. For example, Bainbridge and Macey (2004) report that the cost of rehabilitating a pipe in ICG 4 is approximately two-thirds the cost of rehabilitating an ICG 5 pipe. Higher unit costs result in an increase in capital expenditure to rehabilitate the same pipe. The resulting higher total expenditures draw down the cash available to the utility and leave less cash for further rehabilitation work. As the rehabilitation rate decreases, it leads to a further rise in the condition grade of the network. It may be noted that the rehabilitation rate can also influence unit cost of rehabilitation directly. For example, economies of scale can be achieved by scheduling larger lengths of pipes for rehabilitation. Conversely, a sudden influx of construction projects in a region may overwhelm the delivery capacity of construction firms. The resulting mismatch between demand and supply can drive up the unit cost of construction. Thus, a causal relationship exists between rehabilitation rate and unit cost of rehabilitation but requires further exploration to be assigned a link polarity. This link is not implemented in the system dynamics model (Section 3.5).

When the impact of network condition grade on maintenance expenditures is considered, two additional reinforcing loops, $\mathbf{R_3}$ and $\mathbf{R_4}$ are revealed. Both of these loops contain the same variables as $\mathbf{R_2}$ except that unit cost of rehabilitation and capital expenditures are replaced. In case of $\mathbf{R_3}$, these are replaced by unit costs of maintenance, maintenance expenditures, and operational expenditures, while for $\mathbf{R_4}$ the replacements are extraneous flows, total sewage flows, sewage treatment expenditures and operational expenditures. When the network deteriorates (condition grade increases), there is an increased need for frequent pipe cleaning (removal of debris and roots) and emergency repairs (of collapsed sewers). This implies higher maintenance expenditures. Similarly, deteriorated pipes are more prone to receive extraneous (infiltration) flows (Schulz et al., 2005). This implies larger volumes of sewage are treated driving up sewage treatment costs for the utility. Both maintenance and treatment expenditures cause operational and in turn total expenditures to rise. The causal relationship between total expenditures and network condition grade has already been described above and is same for $\mathbf{R_3}$ and $\mathbf{R_4}$ as well.

The dotted causal links involving sewage volumes indicate that these are not implemented in the system dynamics model (Section 3.5). These relationships are beyond the scope of this study (Section 3.3) but are nonetheless presented for completeness of the CLD. Higher volumes of sewage increase the cost of treatment through two mechanisms. The first one is fairly obvious that more sewage implies higher costs because of higher consumption of chemicals and energy for pumping. Additionally, regulatory authorities require that if a sewage treatment plant discharges treated flows that are too high for the assimilative capacity of the receiving water body then additional and costlier treatment processes are required (Region of Waterloo, 2010). The stringent treatment levels can offset the cost savings derived from economies of scale. In addition to these two categories of treatment plant operational expenditures, additional expenditures are also incurred due to capital depreciation charges of the treatment plant. Explaining those capital charges involves unit construction costs of treatment plant, financing mechanisms, service life of treatment plant equipment, and amortization period. That on its own constitutes an interesting dynamic system to be further investigated but is beyond the scope of this study. Finally, unit cost of sewage treatment charged to the wastewater network utility increases with increasing treatment plant expenditures and decreases with higher volumes of sewage. The later involves a time delay because in some Canadian municipalities, unit sewage treatment costs are determined on the basis of preceding five year average of sewage flows instead of current year flows (Region of Waterloo, 2010).

3.4.2 Feedback loop involving consumer behaviour

Water consumption, utility's revenue, and sewage fee are interconnected to form a reinforcing loop, shown as $\mathbf{R_5}$ in Figure 3.4. A water utility is financially self-sustaining when its revenues equal or exceed its expenses. When revenues are not sufficient then revenue shortfall grows. To eliminate the revenue shortfall, the utility must increase sewage fee. Consumers can respond to an increase in sewage fee by reducing water consumption. A decrease in water consumption will further reduce revenues. It should be noted that this self-reinforcing feedback loop may not operate indefinitely as constraints on one or more parameters around the loop can be triggered that stops growth. For instance, once the minimum water demand (due to social or technological limits) is reached, further decreases will not occur regardless of sewage fee increases.

Both $\mathbf{B_{x1}}$ and $\mathbf{B_{x2}}$ are balancing feedback loops involving sewage fee. Each operates to constrain the self-reinforcing behaviour of loop $\mathbf{R_5}$. Loops $\mathbf{B_{x1}}$ and $\mathbf{B_{x2}}$ represent the limitations imposed by the socio-political environment on utility managers. In Canada, urban water and wastewater systems are publically owned. Therefore, sewage fee increases have to be approved by municipal councils which are sensitive to voters' feedback. When sewage fees are high, it causes a reduction in customers' willingness to accept a further fee hike. Reduced fee hike acceptance implies that future sewage fees will be lower than what would otherwise have been. One response of consumers to rising fee levels is to cut back their consumption. But once they have reduced discretionary consumption (such as outdoor use), further reductions have an attached cost such as investing in water conserving appliances and plumbing fixtures. This means that as water demand decreases toward minimum demand, acceptance of fee hikes decreases as well.

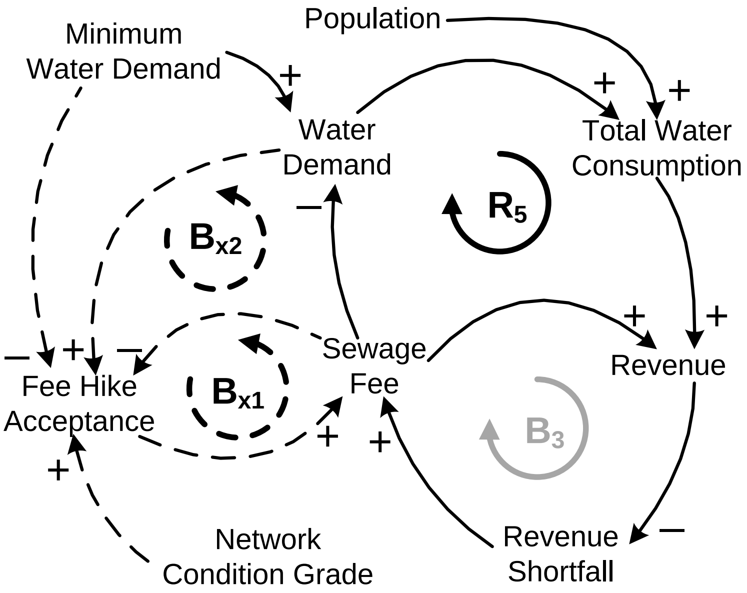


Figure 3.4: Feedback loops involving consumer behaviour.

Loops $\mathbf{B_{x1}}$ and $\mathbf{B_{x2}}$ are also connected to loop $\mathbf{B_1}$ (Figure 3.3) through the network condition grade. It has been reported that consumers are willing to pay positive amounts of money in return for a water supply service that is more reliable and less prone to service interruptions (MacDonald et al., 2003; and Rollins et al., 1997 cited in Renzetti, 1999). Assuming that the same is true for wastewater services, it can be stated that since a deteriorated infrastructure system will cause increased service interruptions, therefore increased deterioration will increase consumers' willingness to accept a fee hike.

Although loops $\mathbf{B_{x1}}$ and $\mathbf{B_{x2}}$ are not implemented explicitly in the system dynamics model (presented in Section 3.5), their influence is indirectly taken into account through a policy lever 'Maximum Allowable Fee Hike Rate' that is explained in Sections 3.5.2 and 3.5.4.

3.4.3 Feedback loops involving a utility's finances

Figure 3.5 shows additional feedback loops which involve a utility's finances. In this figure, loop $\mathbf{B_2}$ is formed due to the interconnection of rehabilitation rate, capital expenditure, total expenditure, available cash, and cash available for rehabilitation. When a utility increases the rehabilitation rate of its network (length of pipes rehabilitated per year is increased), an increase in capital expenditures results. The increase in capital expenditures eventually leads to lower rehabilitation rate (as explained for loop $\mathbf{R_2}$ above in Section 3.4.1). Thus a balancing loop $\mathbf{B_2}$ is shown to exist.

Another balancing feedback loop ($\mathbf{B_3}$) exists among revenue, revenue shortfall and sewage fee. As revenue shortfall grows, the sewage fee is increased. A higher sewage fee implies greater revenue and hence a decrease in the revenue shortfall.

Cash shortfall, debt issuance and available cash together constitute balancing feedback loop $\mathbf{B_4}$. When the utility's cash shortfall (arising due to a mismatch between available cash and required cash) increases, the utility can issue debt. Debt issuance increases available cash and in turn cash shortfall is reduced.

Water utilities can be constrained in the amount of total debt that they carry through legislative mandates. For example, in the Province of Ontario, water utilities are restricted from carrying debt that results in annual debt service charges (repayment of principal plus interest) exceeding 25% of their annual revenues (Kitchen, 2004). Taking this limitation into consideration, debt issuance combines with total debt, debt service, and unused debt capacity to form another balancing feedback loop $\mathbf{B_5}$. This loop implies that increasing debt issuance causes the total debt to grow. An increased total debt means higher annual expenditures on debt service. Increased debt service means that the utility's ability to issue further debt is decreased or its unused debt capacity is reduced. Reduction in unused debt capacity means that further debt issuance is lower than would be the case otherwise.

Debt issuance also forms part of the reinforcing loop $\mathbf{R_5}$. As stated earlier, higher debt issuance leads to increased debt service. Increased debt service means higher total expenditures. Increased total expenditures mean that utility's cash requirement also rises. This causes the cash shortfall to grow, finally leading to even more debt issuance.

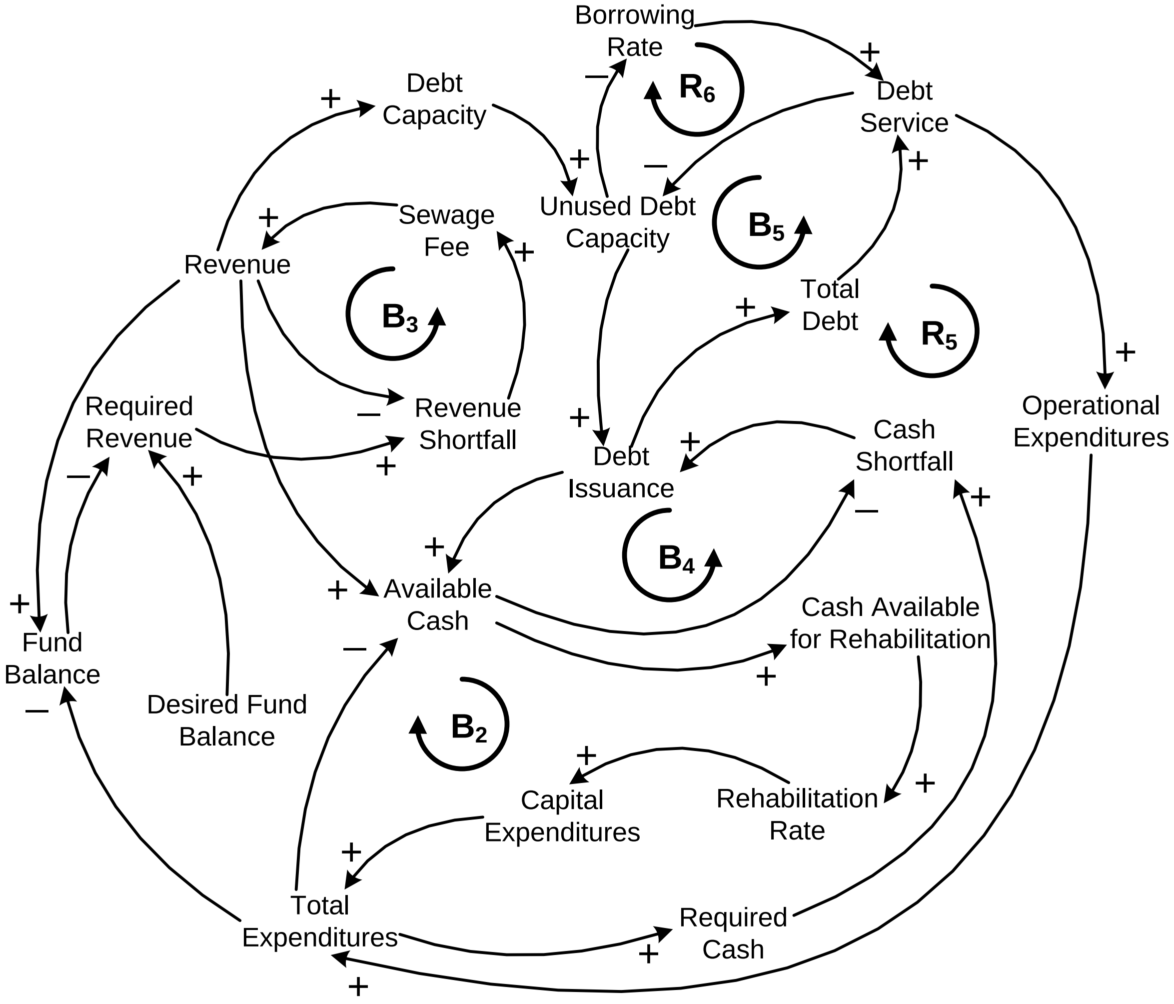


Figure 3.5: Feedbacks involving finances of wastewater network management.

Finally, a reinforcing loop, **R_6** exists along unused debt capacity, borrowing rate and debt service. This loop shows that the interest rate at which a utility borrows is a function of its existing debt. If the utility is already carrying a high debt, then its debt servicing obligations are high. Higher debt service implies that its unused debt capacity decreases. With a lower unused debt capacity, the utility will be able to borrow further at higher interest rates. Higher borrowing rates imply higher interest payments thus increasing debt service charges.

The presented causal loop diagram can be utilized for improving a utility's performance. Dell (2005) states that the organizational structure of water and wastewater utilities acts as a barrier to better performance. Departments within a utility are organized according to functional area but effectively transform into organizational silos. Within such silos, the focus is more on self-interests rather than the interest of the utility as a whole. This creates problems such as duplication of efforts, limited scope for efficiency gains, and poor decision making processes (Dell, 2005). A causal loop diagram can be employed to visualize interrelationships that span across departmental boundaries. Thus, the potential consequences of an action can be anticipated (Wolstenholme, 1999). This is especially important when action originates in one department and consequences are felt in other department(s). Eventually, the causal loop diagram can help lead to an improved understanding of the complex challenges facing the utility and development of a shared vision to tackle those challenges.

To quantitatively assess influence of the interacting feedback loops identified above, a mathematical model is needed. In the following section, a model is developed using the system dynamics approach.

3.5 System Dynamics Model for Management of Wastewater Collection Networks

System dynamics (Forrester, 1958) is a well-established methodology that provides a theoretical framework and concepts for modelling complex systems. It has been applied to a wide range of problems in social and physical sciences (Forrester, 1969; Sterman, 2000; Ford, 1999). A few examples of its application are discussed in Section 3.2. Recent examples of its application in Civil Engineering include; water resources (Winz et al., 2009), construction management (Menassa and Pena-Mora, 2010), solid waste management (Sudhir et al., 1997), highway management (Fallah-Fini et al., 2010), transportation (Haghani et al., 2010), sustainable concrete technology (Nehdi et al., 2004), and building design (Thompson and Bank, 2010).

The basic building blocks for system dynamics models are; stocks, flows, converters, and connectors (Figure 3.6). Stocks represent accumulations - both physical and non-physical. Examples of physical stocks are inventory of pipes, amount of water in a reservoir, etc. A non-physical stock is the consumer’s level of satisfaction with a water utility service. Stocks represent the ‘traces’ left by an activity. Material in a stock exists at a given point in time and persists even when activities end. Flows represent activities or actions in a stock that transport quantities into or out of a stock instantaneously or over time. Examples of flows are daily consumption of water, rate at which pipes move from one condition grade to another, monthly revenues or expenditures of a utility, etc.

Mathematically the relationship between stocks and flows can be described using the following integral form (Sterman, 2000):

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

where t_o is the initial time, t is the current time, $Stock(t_o)$ is the initial value of the stock, $Inflow(s)$ and $Outflow(s)$ are flow rates into and out of a stock at any time s between the initial time t_o and current time t. $Inflow(s)$ and $Outflow(s)$ have the units of $Stock(t)$ divided by time. Connectors (arrows noted in Figure 3.6) establish relationships among various elements of the model and move information as inputs for decisions or actions. Converters house graphical and built-in functions (circles in Figure 3.6). Examples of converters are pipe deterioration curves and demand curves for water usage.

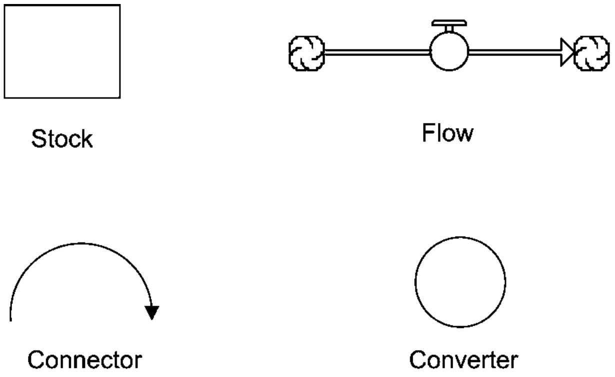


Figure 3.6: Building blocks of system dynamics models.

Using the above building blocks, a system dynamics model for management of wastewater networks is developed using research version 7.0.2 of Stella® software (Richmond, 2001). Stella® is an object oriented modelling and simulation software used extensively for building system dynamics models. The model has three sectors; (1) finance sector, (2) wastewater collection network sector, and (3) consumer sector. Salient features of these sectors are described in the following sections. Full details of the model including equations for all model objects are provided in Appendix B.

3.5.1 Wastewater collection sector

The wastewater collection sector is shown in Figure 3.7. This sector includes stocks representing wastewater pipes with common characteristics such as internal condition grade, material, age, and diameter. To avoid clutter, stocks for the five internal condition grades ($SwPipes\ Grade_i$ where $i = 1$ to 5) but with different combinations of pipe material, diameter, etc. have been shown as stacked on top of each other. Flow $NewPipes\ Installation$ represents expansion of the network to service population growth. These new pipes start in stocks $SwPipes\ Grade_1$.

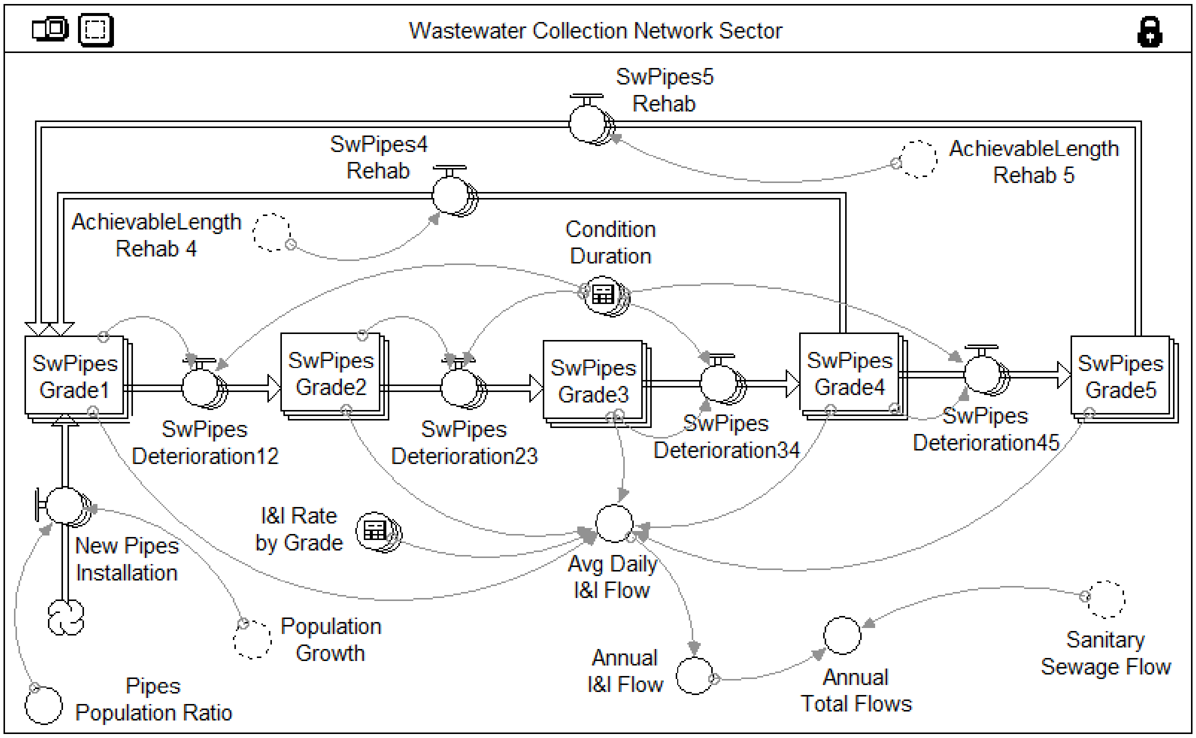


Figure 3.7: Wastewater collection sector in Stella®.

Deterioration of pipes is represented as flows $SwPipes\ Deterioration_{ij}$ ($i = 1,2,3,4$ and $j = i + 1$). The time duration for which a pipe resides in a lower enumerated ICG stock before moving into the next higher ICG stock can be estimated using a deterioration model (Younis and Knight, 2010a,b; Baur and Herz, 2002; Wirahadikusumah and Abraham, 2003). These duration times are specified by the user in the converter $Condition\ Duration$.

Flows $SwPipes_i\ Rehab$ ($i = 4$ and 5) represent rehabilitation of pipes. For this study, it is assumed that only pipes in ICG 4 and ICG 5 are rehabilitated. These flows move pipes from stocks representing ICG 4 and ICG 5 to stocks representing ICG 1. The actual lengths of pipes moving through the rehabilitation flows is controlled by converters $Achievable\ Length\ Rehab$ 4 and $Achievable\ Length\ Rehab$ 5, based on a specified target length of pipes (see Section 3.5.4) to be rehabilitated annually. Depending upon the cash available for rehabilitation each year, the model calculates the annual lengths for rehabilitation. When cash availability is a limiting factor, the model gives priority to rehabilitation of ICG 5 pipes.

Extraneous flow volumes (infiltration and inflows – I&I) are calculated based on the internal condition grade of pipes. For each ICG, converter $I\&I\ Rate\ by\ Grade$ contains user specified values for daily infiltration volume per unit length of pipes. These values are multiplied by the corresponding lengths of pipes in each ICG to determine daily infiltration volumes for the whole network. Daily infiltration volumes are converted to annual flow volumes and are combined with sanitary sewage volume to obtain total annual flow volumes. Calculation of sewage volume is described in Section 3.5.3.

The average network condition grade is determined using Equation 3.2:

$$Average\ Condition\ Grade = \frac{\sum_{i=1}^{5} i \times SwPipeLengths_i}{\sum_{i=1}^{5} SwPipeLengths_i} \tag{3.2}$$

where $SwPipeLengths_i$ represents length of pipes in internal condition grade i.

Detailed equations governing this sector are presented in Appendix B.

3.5.2 Finance sector

The finance sector of the model is shown in Figure 3.8 and includes four key variables; sewage fee, profit/loss account, available cash account and debt. Each of these variables has associated stock-flow structures and these structures are interconnected to other variables.

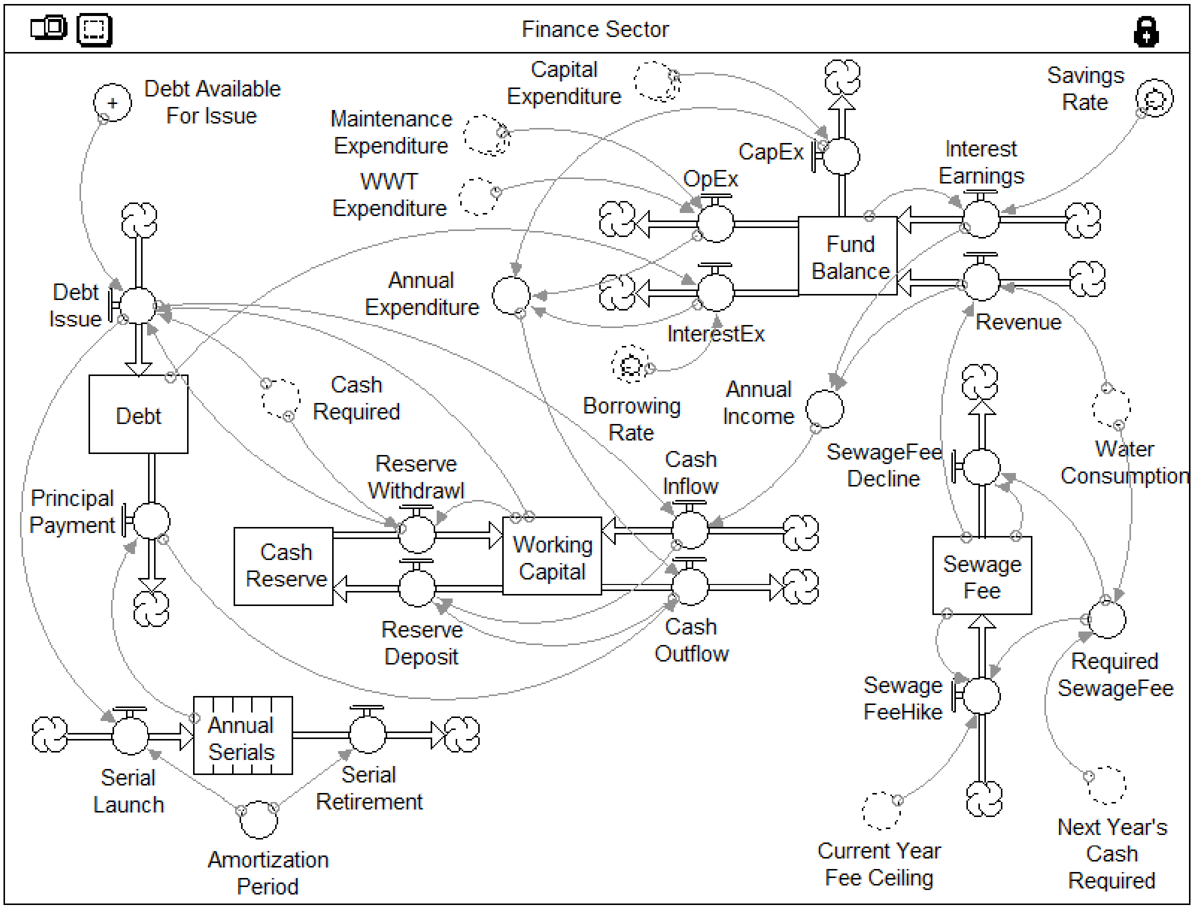


Figure 3.8: Finance sector of the model in Stella®.

Stock *Sewage Fee* tracks the price per unit of volume of water charged to customers for receiving wastewater services. A financially self-sustaining utility implies that it has sufficient revenues to pay for all expenditures. At each time step, next year's revenue requirements are calculated such that sufficient cash is available to pay for expenditures and to maintain profit/loss account at desired levels. The sewage fee required to yield this revenue is calculated based on the prevailing (last time step's) water consumption rate. Stock *Sewage Fee* is then adjusted using flows *Sewage Fee Hike* and *Sewage Fee Decline*. If the current value of *Sewage Fee* is higher than the required sewage fee (as calculated for next year's revenue requirements) then a downward fee adjustment is implemented. Upward adjustments in $Sewage\ Fee$ is limited not to exceed user defined year-to-year fee hike rate (Section 3.5.4).

The profit/loss account of the utility is represented by the stock $Fund\ Balance$. This stock represents the net surplus or deficit that the utility may accumulate over time. The value of $Fund\ Balance$ can fluctuate between positive and negative over time, but the objective is to maintain it at a user defined level. As mentioned above, this is accomplished by continuously adjusting $Sewage\ Fee$ over the course of simulation. Consistent with the categorization scheme of Figure 3.2 $Fund\ Balance$ has two inflows for income and three outflows for expenditures.

The flow $Revenue$ is calculated as a product of stock $Sewage\ Fee$ and converter $Water\ Consumption$. The latter belongs to the consumer sector and is explained in Section 3.5.3. $Interest\ Earnings$ is calculated using user specified $Savings\ Rate$ for positive values of stock $Fund\ Balance$ maintained over a simulation time step. $CapEx$ is calculated by multiplying lengths of pipes that are rehabilitated (information obtained from wastewater collection network sector) with the corresponding unit costs of rehabilitation. Outflow $OpEx$ sums up maintenance and sewage treatment expenditures while $InterestEx$ represents the interest payments on outstanding debt.

The amount of cash available to the utility is represented by stock $Working\ Capital$. Cash flow into this stock consists of the utility's annual income (revenue and interest earnings) and the amount of debt issued during any year. Cash available with the utility can be spent on various activities. These include annual expenditures as described above and re-payment of the principal portion of loans previously obtained. When the available cash is allocated to various functions, repayment of loans and operational expenditures have a higher priority than capital expenditures. Hence depending upon the amount of available cash, capital expenditures can be lower (or even zero) than the planned amounts in a given year. On the other hand, when available cash exceeds cash outflows during a year, the excess amount is transferred to stock $Cash\ Reserve$ to be utilized next year. It should be noted that stock $Working\ Capital$ cannot have negative values. In comparison, stock $Fund\ Balance$ can have both positive and negative values.

The amount of total debt carried by the utility is represented by stock $Debt$. At each time step, the amount of cash available and cash reserve is compared with the cash requirement. If cash required is more than the available cash then debt is issued to make up for the shortfall. However, debt issuance is subject to the constraint of debt capacity of the utility. This means that new debt can only be issued as long as annual debt service (principal repayment plus interest charges) does not exceed a specified fraction of utility's revenue. In this study it is assumed that the utility borrows funds by issuing long-term debentures known as 'straight serials'. Such serials require annual principal payments of equal amounts and are preferred by municipalities over other types of debentures (Fortin et al., 2002). In the model when new debt is issued, the required serial for its repayment is calculated by dividing the amount of issued debt by the $Amortization\ Period$. This value of serial is added to the stock $Annual\ Serials$ which represents the utility's annual obligation for principal payments of all outstanding debts. A serial added to stock $Annual\ Serials$ remains for the duration of $Amortization\ Period$ after which it is removed through the outflow $Serial\ Retirement$. The outflow $Principal\ Payment$ reduces stock $Debt$ by an amount equal to the value of stock $Annual\ Serials$. Detailed equations for this sector are presented in Appendix B.

3.5.3 Consumer sector

The amount of sewage generated by consumers is a function of water consumption in the consumer sector (Figure 3.9).

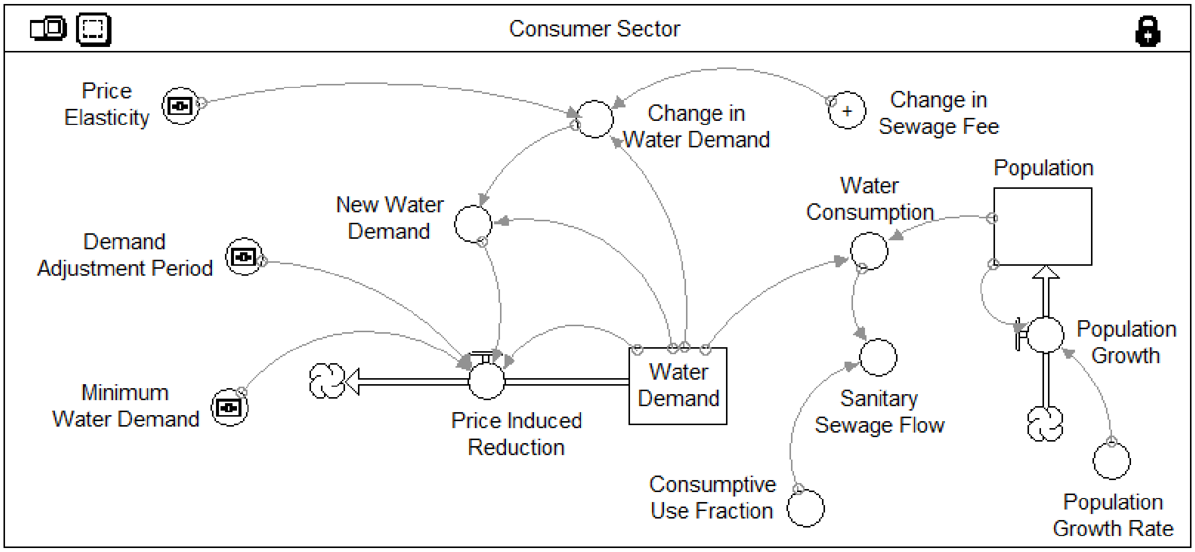


Figure 3.9: Consumer sector of the model in Stella®.

The daily volume of water consumed per person is determined using the stock $Water\ Demand$. This stock can change through its outflow $Price\ Induced\ Reduction$ which is a function of

Price Elasticity of water demand, *Sewage Fee*, *Minimum Water Demand* and *Demand Adjustment Period*. Lipsey and Chrystal (1999) define price elasticity of demand as the percentage change in a demanded quantity of a good divided by the corresponding percentage change in its price. Thus, the flow *Price Induced Reduction* decreases *Water Demand* when sewage fee increases. Because water utilities usually charge for wastewater services on the basis of consumed water, the rationale for the water demand decrease is that customers will implement water conservation measures (i.e. retrofitting of plumbing fixtures and the installation of water conserving appliances) to reduce their sewage bills as sewage fees increase. It is assumed that once water conservation measures are implemented, they are permanent. Therefore, water demand is assumed to remain constant at its minimum attained level even when the sewage fee decreases. Price induced changes in water consumption are not instantaneous and occur over time (Fortin et al., 2002). Therefore, water demand reduction is estimated using the *Price Elasticity* over a *Demand Adjustment Period*. The converter *Minimum Water Demand* is used to set a minimum water demand limit.

Total water consumption is the product of the average per capita water demand and population served by the utility. The volume of sewage produced is calculated by subtracting from the total water consumption the fraction of water that is not returned to the wastewater collection network. This fraction, named *Consumptive Use Fraction*, represents water uses such as irrigating lawns, outdoor uses where used water is allowed to drain into storm sewers, and evaporation losses from swimming pools. Detailed equations for this sector are presented in Appendix B.

3.5.4 Policy levers

For this study, the following policy levers are developed to test various network management strategies:

1. the maximum allowable fee hike rate;
2. whether ICG 4 pipes are rehabilitated;
3. the preferred network rehabilitation rate;
4. the maximum acceptable ICG 5 fraction of pipes in the network;
5. the desired elimination period for ICG 5 fraction of pipes; and
6. the debt capacity.

Maximum allowable fee hike rate is the maximum percentage by which sewage fee is allowed to increase annually. It acts as a constraint on flow $Sewage\ Fee\ Hike$ (Section 3.5.2) and is included to reflect the influence of feedback loops $\mathbf{B}_{\mathbf{x1}}$ and $\mathbf{B}_{\mathbf{x2}}$ (Section 3.4.2). Water utilities are not allowed to finance their operational expenditures through borrowing (Kitchen, 2002). Therefore, when revenues and cash reserves are not sufficient then the sewage fee is increased so that operational expenditures can be paid for. In such cases the constraint imposed by maximum allowable fee hike rate is overridden.

Users can specify whether pipes in ICG 4 are rehabilitated or not. This allows one to compare the impact of ‘run to failure’ management policies (ICG 4 pipes are not rehabilitated) with proactive rehabilitation management policies (ICG 4 pipes are rehabilitated). Specifically this involves studying the influence of loop $\mathbf{R}_2$ (Section 3.4.1).

Preferred network rehabilitation rate is the percentage of total network length that a user specifies to be rehabilitated annually. The actual rehabilitation rate can be less than this preferred rate if sufficient cash is not available to carry out rehabilitation or there are simply not enough pipes in ICG 4 (if slated for rehabilitation) and ICG 5.

Maximum acceptable ICG 5 fraction of pipes is the percentage of network length that is tolerated to be in ICG 5. As long as the actual fraction of ICG 5 pipes is below this specified threshold, rehabilitation proceeds at a rate up to the preferred rehabilitation rate. But when the threshold is crossed, the model calculates a new value for rehabilitation rate such that all ICG 5 pipes are rehabilitated over a desired elimination period (next policy lever). The financing constraints still remain in effect. This policy lever is used to simulate a crisis driven management approach where the network is allowed to deteriorate until a point that it can no longer be ignored. The maximum acceptable ICG 5 fraction can be set to any value from 0 to 100% of the network. The desired elimination period for ICG 5 pipes is meaningful only in conjunction with the previous policy lever and can be assigned a value of 1 or more years.

Debt capacity is the percentage of total annual revenue up to which debt service charges are allowed to increase. Setting it to zero implies a ‘pay as you go’ financing strategy where all expenditures are paid for through current revenues and no debt is issued. Its upper limit is often set by regulations (Kitchen, 2002; Bird and Tassonyi, 2001).

Finally, it should be noted that in addition to the model objects described in this section, the complete model contains several auxiliary objects to perform all needed calculations. A listing of all the model objects and equations is provided in Appendix B.

3.6 System Dynamics Model Application

In this section the data requirements and uses of the presented system dynamics model are discussed.

3.6.1 Data requirements

Some of the data required for running the system dynamics model is available with certain municipalities. For others the user may assume values based on expert judgment, refer to published literature, or carry out surveys. The following discussion describes data required in each sector of the model.

3.6.1.1 Wastewater collection network

This sector requires information about inventory of pipes along with their attributes. The level of detail for pipe attributes depends upon the deterioration model that the user wishes to use. If an age based deterioration model is used then only information about the current internal condition grades and ages of pipes is sufficient. Other models (Younis and Knight, 2010a,b; Baur and Herz, 2002) require additional details such as pipe material, diameter, and surrounding soil characteristics.

To allow estimation of inflow and infiltration volumes, the average daily volume of extraneous flows per unit length of pipe for each category of pipe stocks is needed. If a user believes that their network has mainly an inflow problem then all pipe stocks can be associated with a uniform value of infiltration rate. This implies that extraneous flows do not depend upon the internal condition grade of pipes. Such a situation can be verified if the water table in the area is lower than pipe elevations and sewage flows at the treatment plant increase immediately after a rainfall event. However, if the water table is generally high or increases in sewage flows persist long after rainfall events then infiltration is the likely cause. In such a case, infiltration rates can be established with the help of flow meters at strategic locations or the total extraneous flow may be calibrated to pipe condition grades using a suitable methodology (for example, Schulz et al., 2005). The lengths of new pipes added to the network for growing population can be estimated using typical ratios such as those published in Burnside (2005).

3.6.1.2 Finance sector

Unit costs of pipe rehabilitation (dollars per metre), both for ICG 4 and 5 pipes are required. Depending upon the pipe classification criteria employed in the wastewater collection sector, these unit costs will be different for pipes of different diameters and materials. Users may estimate these unit costs from their own tender records using a methodology such as that developed by Unger et al. (2011) or rely on other published sources such as RS Means (www.rsmeans.com).

Unit costs of maintenance (dollars per metre per year) for each category of pipe stocks in the wastewater collection sector are needed. Ideally these should be estimated from a utility's historic maintenance costs. But in many cases, the historic costs may be aggregated and not linked to pipes of specific attributes. In such cases, one can refer to studies such as Burnside (2005).

Future values of unit price of wastewater treatment can be obtained from the operator of wastewater treatment plant while taking into account its future operational and capital expenditure requirements for various levels of treatment plant capacities.

Savings rate depends upon the utility's preference for the specific kinds of financial instruments in which it invests its cash reserves. It is most likely that a utility invests in risk free instruments such as Bank of Canada T-bills and the corresponding rate of return can be used as savings rate in the model. Borrowing rate depends upon the market in which the utility seeks to borrow as well as its own credit rating (Moody's, 1999). In the Province of Ontario, public water utilities have access to loans through a provincial crown corporation which publishes its lending rates (Infrastructure Ontario, 2011).

The developed model has the capability to inflate the various unit prices using their respective inflation rates. Cost inflation indices for specific purposes are generally available. Consumer price index can be used for inflating administrative costs, sewer pipe construction inflation rate developed by Unger et al. (2011) can be used for inflating unit costs of rehabilitation.

3.6.1.3 Consumer sector

This sector requires information such as current water demand, price elasticity of water demand, minimum water demand, demand adjustment period, current population and population growth rate. Information about current water demand, current population, and expected population growth rate is available in most cases. The remaining three need to be estimated through consumer and market surveys. Estimation of price elasticity of demand is the subject of many studies (Agthe and Billings, 2003). Reported values of price elasticity vary considerably in range and selecting a value needs careful evaluation of factors such as climate and socio-economic conditions to determine applicability to a particular case. Choosing a value for demand adjustment period involves consideration of whether the price elasticity of demand captures short-run or long-run effects. Minimum demand of water can be selected based on expert judgment while taking into account water demand values in other cities of comparable characteristics.

3.6.2 Model uses

Figures 3.7, 3.8 and 3.9 present snapshots of the structural level of the developed model. At this level, model objects are connected to each other and equations (Appendix B) are written for all the model objects. For policy testing and formulation, a user friendly interface is developed (Figure 3.10). This interface can be used to input required data and set policy levers using tables, knob and slider input devices. Results are displayed graphically as well as stored in tabular format for detailed inspection. These functionalities allow users to quickly alter values of various parameters for conducting ‘what if’ analysis without the need to make changes at the structural level of the model.

Significant progress has been made in developing decision support tools for managing wastewater collection networks. These include deterioration models and optimization algorithms for efficient use of resources. To fully exploit their potential benefits, these tools need to be used in a holistic framework where the underlying assumptions (for example assumed streams of capital expenditures) are endogenous to the system.

The model can be used to develop short- and long-term management plans for wastewater collection networks. Different financial and rehabilitation strategies can be devised using the policy levers discussed in Section 3.5.4. The impact of these strategies on system performance can then be simulated using the model. Alternative strategies can be compared in terms of performance indicators, such as, fractions of pipes in various internal condition grades, average condition grade of the network, sewage fee, water demand, total sewage and extraneous flows, annual and cumulative values of various expenditure categories, revenues and fund balance of the utility.

The impact of various financing strategies can be evaluated in terms of whether these assure financial sustainability. Sewage fees can be examined in terms of consistency, stability and affordability. Because of their long service life, wastewater collection networks typically serve several generations. An important consideration in developing strategic plans is to check how the costs (fees) and benefits (service performance levels) are shared among different generations. This can be easily accomplished by running the model for various scenarios and simulation periods (20, 50, 100 years).

Ontario’s Ministry of the Environment (2007b) recommends close collaboration among engineers, accountants, auditors, utility staff, and municipal council for development of the mandated financial plans. Similarly, Dell (2005) recommends customer involvement in establishing service level targets. Falp and Le Masurier (2009) report that customers who are aware of their water/ sewerage company(ies)’ responsibilities, are more likely to see water and wastewater services as good value for money. The presented model can be utilized in achieving these important goals.

3.7 Conclusions

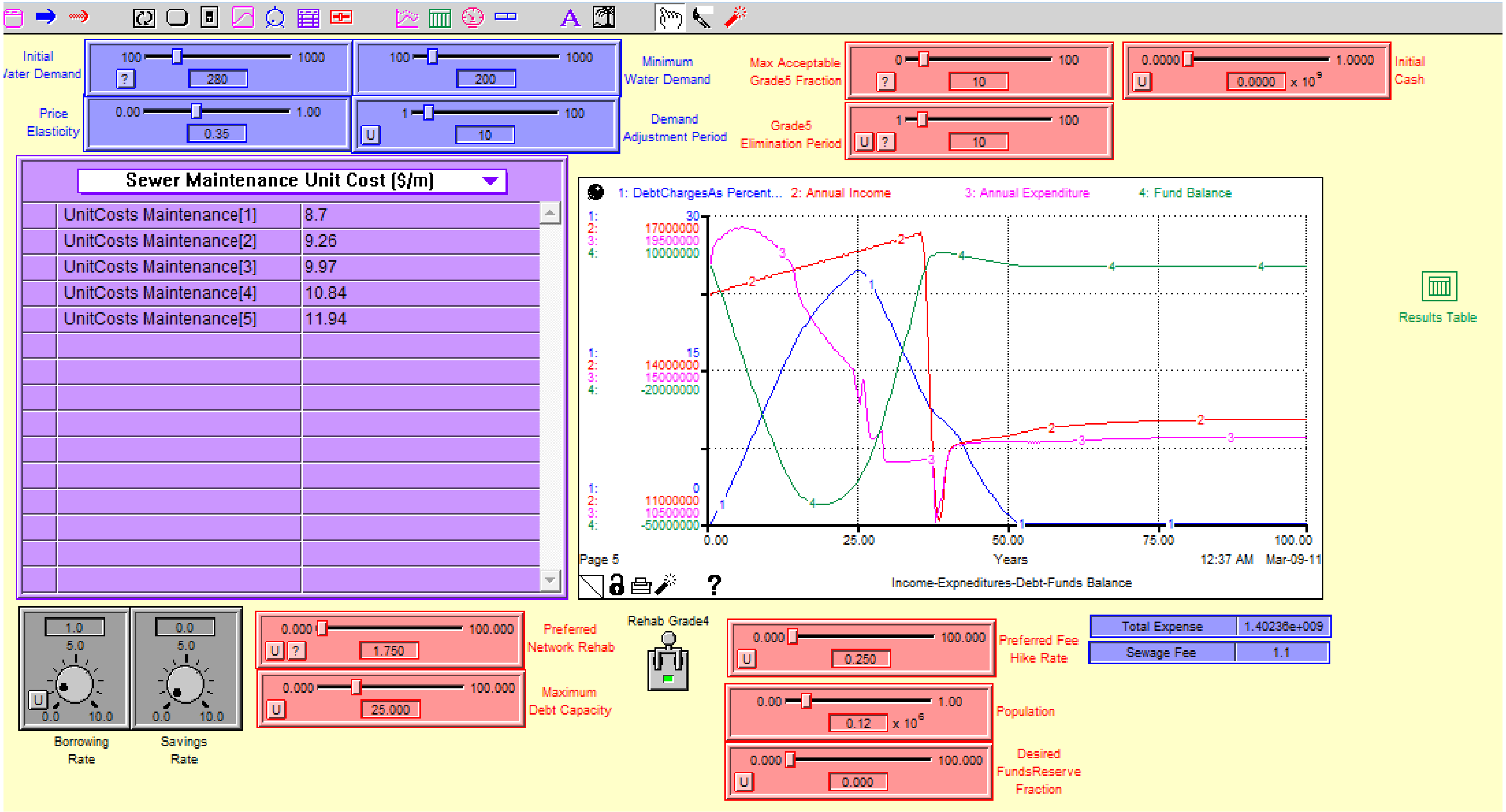
This study makes two unique contributions to the body of knowledge. First, a detailed causal loop diagram for management of wastewater collection networks is developed. Second, the qualitative causal loop diagram is operationalized as a decision support tool using the system dynamics approach.

The presented causal loop diagram is the first known attempt to lay out the interrelationships among system components using a formal technique. These interrelationships are based on the authors’ understanding of the system developed through literature review, extensive interactions and research collaboration with industry professionals, and field experience. By presenting the causal loop diagram, it is exposed to be critiqued and improved upon, thus advancing the state of knowledge.

The causal loop diagram can be used to easily follow how perturbation of one system component reverberates throughout the system. This can especially be useful to mitigate effects of the silo-based organizational culture prevalent in water utilities.

An important contribution of the causal loop diagram is that it establishes the existence of several interacting feedback loops. These feedback loops demonstrate that management of wastewater collection networks constitutes a complex dynamic system for which traditional management tools used in the area are deemed inadequate.

The presented system dynamics model is the first known decision support tool to quantitatively simulate the influence of interrelationships and feedback loops in wastewater collection network management. The model can be used to develop financially sustainable management policies, thereby helping utilities meet their regulatory obligations. Utility and functionalities of the system dynamics model, the next chapter discusses its implementation for a case study.



Sewer Maintenance Unit Cost ($/m)

UnitCosts Maintenance[1]	8.7
UnitCosts Maintenance[2]	9.26
UnitCosts Maintenance[3]	9.97
UnitCosts Maintenance[4]	10.84
UnitCosts Maintenance[5]	11.94

Initial ater Demand	100	1000	280
Minimum Water Demand	100	1000	200
Price Elasticity	0.00	1.00	0.35
Demand Adjustment Period	1	100	10
Max Acceptable Grade5 Fraction	0	100	10
Grade5 Elimination Period	1	100	10
Initial Cash	0.0000	1.0000	0.0000 x 10^9
Borrowing Rate	0.0	10.0	1.0
Savings Rate	0.0	10.0	0.0
Preferred Network Rehab	0.000	100.000	1.750
Maximum Debt Capacity	0.000	100.000	25.000
Preferred Fee Hike Rate	0.000	100.000	0.250
Population	0.00	1.00	0.12 x 10^6
Desired FundsReserve Fraction	0.000	100.000	0.000

Total Expense	1.40236e+009
Sewage Fee	1.1

Figure 3.10: User interface level of the model in Stella®.

Chapter 4

Financially sustainable management strategies for urban wastewater collection infrastructure: implementation of a system dynamics model

4.1 Introduction

In the Province of Ontario, as in the rest of Canada, the majority of urban water supply and wastewater collection systems are owned and operated by municipal governments (Bakker and Cameron, 2005). Historically, user fees charged for water and wastewater services do not reflect the full costs required to provide these services. Thus, user fee based revenues are not sufficient to cover both operational and capital expenditures (Renzetti, 1999). The balance is typically financed through grants received from higher levels of government and other sources of municipal revenue such as property taxes and other fees. Subsidization of water and wastewater services is reported to be responsible for overconsumption and installation of excess capacity (Swain et al., 2005). Recently, two important regulations have come into force that impact the financing of municipally owned water and wastewater systems. One is the Public Sector Accounting Board (PSAB) statement PS 3150 and the other is the Province of Ontario Regulation 453/07. PS 3150 requires all municipalities in Canada, starting in January 2009, to report all tangible capital assets along with their depreciation on financial statements (CICA, 2007). Ontario Regulation 453/07 requires all public utilities to prepare and submit yearly reports on current and estimated future condition of water and wastewater infrastructure and long-term financial plans based on the principle of financial sustainability.

In Chapter 2 it was stated that the new regulatory environment adds to the complexity of managing water and wastewater systems, and highlight inter-relationships and feedback loops among physical infrastructure, finance, and social components of water and wastewater systems. Specifically, it is shown that inter-relationships and feedback loops have significant impacts on user fees, life-cycle costs and the physical condition of the system. It is pointed out that current decision support tools for the management of water and wastewater systems do not capture the complexity of these systems. To address this knowledge gap, a system dynamics model for management of wastewater collection networks is developed and presented in Chapter 3. The model includes various policy levers which allow formulation and testing of alternative financing and rehabilitation policies for wastewater collection networks within the paradigm of financial self-sustainability.

The goal of this study is to demonstrate the utility of the system dynamics model as a decision support tool that can assist utilities to manage wastewater networks in a financially sustainable manner while meeting customer expectations of service performance levels. To achieve this goal, implementation of the model for a demonstration case study is presented. A central issue that is explored is whether the benefits gained in improving the service performance level of the network by increased spending on capital works at an early time when facilitated by issuing debt can offset increased expenditures needed to pay for interest on the debt. This particular issue is explored by introducing a "city" in which there is a large backlog of internal condition grade 4 (advanced deterioration state but collapse is not imminent) pipes that will require replacement in the near future, while a manageable 1.5% of network is in internal condition grade 5 (collapse imminent). This is typical situation for several municipalities in Ontario. Issuance of debt allows proactive rehabilitation of internal condition grade (ICG) 4 pipes rather than just focusing on reactive replacement of collapsed ICG 5 pipes. Financial sustainability is evaluated by tracking the utility's fund balance over a 100-year planning horizon.

Specific outcomes for this study are:

- presentation of a methodology to parameterize the demonstration model using available utility data;
- demonstration of the significance of interrelationships between system variables on a system's performance indicators such as total life-cycle costs, internal condition grade of pipes, sewage fees; and
- exploration of alternative financially sustainable management strategies for operating a wastewater network that involve the trade-offs between maintaining a strict 'zero fund balance' with no borrowing, versus issuing debt to accelerate a capital works program.

The following sections set the contextual framework by presenting the demonstration case study background information and assumptions. In Section 4.3, a methodology for parameterization of key model variables is explained. Results of the model application are presented and discussed in Section 4.4. Conclusions are drawn in Section 4.5.

4.2 Case Study Description

4.2.1 The case study 'city'

Over the past three years, utility water and wastewater data was collected to build, validate and test a system dynamics model. Review of this utility data found it to be insufficient to parameterize all model variables. For this case study, existing utility data is synthesized to represent a typical (but not a specific) medium size city in southern Ontario, Canada. The relevant features of this hypothetical "city" and its wastewater system are presented below.

The city is assumed to have a population of 120,000 people who are served by separate sanitary and storm sewer systems. The city's water department (hereafter referred to as the "utility") manages the water distribution and wastewater collection networks. Water and wastewater treatment are managed by an upper tier of municipal government. This shared but differentiated arrangement for water and wastewater services is typical for many municipal governments in Ontario.

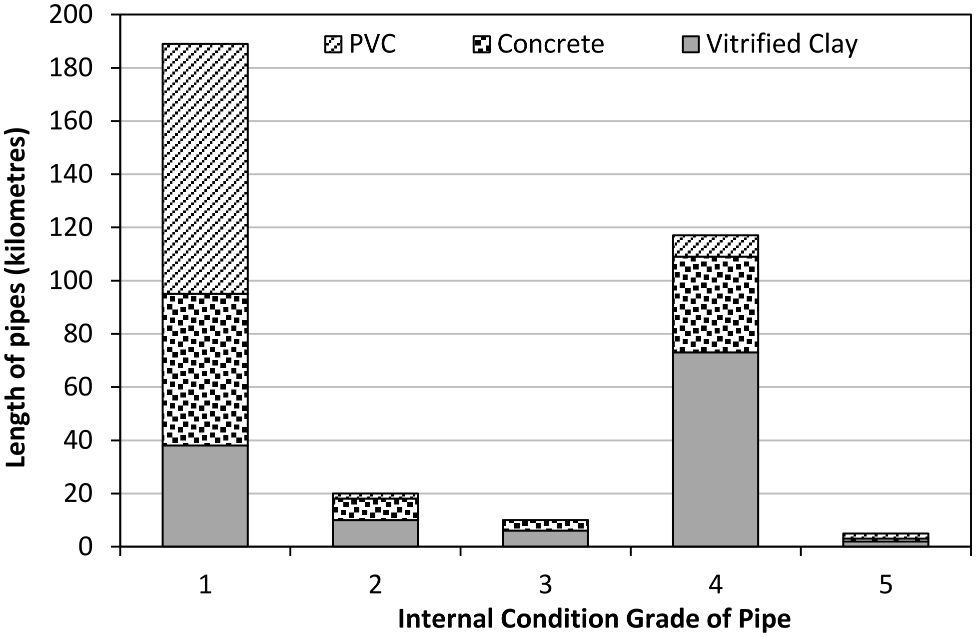


Figure 4.1: Profile of the wastewater collection network for the case study.

The wastewater collection network is assumed to be 341 kilometres long and is comprised of pipes made of vitrified clay, concrete and polyvinyl chloride (PVC). Almost half (156 kms) of the network is less than 25 years old, and no pipe is more than 75 years old. Figure 4.1 presents the lengths of pipes according to pipe material and internal condition grade (ICG). Internal condition grades are assigned according to the protocol developed by the Water Research Centre (WRc) in the United Kingdom (WRc, 2001). Figure 4.1 shows that more than half the network (55%) consists of ICG 1 (excellent condition) pipes and 1.5% is in ICG 5 (collapsed or imminent collapse condition). Another important feature is that 34% of the network is in ICG 4. While the ICG 4 pipes are currently in serviceable condition, they will deteriorate to ICG 5. Thus, there is a large cohort of pipes expected to cause service disruptions in the near future. The utility is assumed to be currently replacing 0.85% of its wastewater collection network every year. Water connections to customers are assumed to be metered and all customers are charged separate water and sewage fees based on consumed water volumes. Both fees are constant volume charges. In other words, customers pay the same price for each unit volume of water consumed and discharged as wastewater.

4.2.2 Assumptions

For this study, the wastewater network length and customer base are assumed constant over the simulation period. This assumption is deemed valid for the case where expansion of the network is funded through development charges. Accordingly, these costs are not passed on through sewage bills.

To simplify the presentation of all costs, the rate of appreciation of costs (inflation rate) and the project depreciation rate (needed to discount all costs to present value) are both assumed to be equal to the risk free rate (r_f), and hence do not need to be specified. Therefore, all costs are given as "present value" and various unit costs (unit sewage treatment charge, unit costs for rehabilitation and unit costs for maintenance of pipes) remain constant over the simulation period. Moreover, it is assumed that the rate at which the utility earns interest on its cash reserves is equal to the risk free rate. Municipal governments in the Province of Ontario can borrow funds at an interest rate which typically is about 1% per annum in addition to the risk free rate. Consequently, a borrowing rate of 1% $(+r_f)$ per annum is adopted assuming that the provincial government facilitates all borrowing through Infrastructure Ontario (2011).

The model is run for a simulation period of 100 years to explore the impact of various management strategies. The choice of simulation period is motivated by recommendations (Heare, 2007; Ministry of the Environment, 2007b) that long-term strategies based on full cost recovery be compared over planning horizons encompassing the service life of physical assets.

4.2.3 Evaluation criteria for management strategies

Alternative management strategies are compared using two criteria - financial and service performance levels.

Financial performance of a management strategy is measured in terms of total (operational and capital) expenditures accumulated over a planning horizon. Thus, a strategy with lower total expenditures (total life-cycle costs) is preferred to other strategies with higher expenditures.

Service performance level is measured using the internal condition grade of pipes. Using the condition rating system of WRc (2001), the service performance of a management strategy is defined in terms of fraction of pipe network in ICG 5. Pipes in ICG 3 and 4 may be structurally deficient but service disruptions due to blockages are most often associated with ICG 5 pipes. Thus, it is assumed that a higher fraction of the network in ICG 5 is indicative of lower service performance.

It should be noted that there can be additional criteria influencing a utility's decision to choose a particular management strategy. Examples include the extent of reliance on debt financing for capital expenditures, reducing energy consumption, and extraneous flow volumes. In this study, management strategies are evaluated only in terms of financial performance (total cumulative expenditures), and service performance (fraction of ICG 5 pipes in the network).

4.3 Parameterization of Model Variables

The following presents the methodology and estimation procedures required to implement the demonstration case study model.

4.3.1 Water consumption

Typical average water consumption in the local region is 280 litres per capita per day (lpcd) and is adopted as the initial water demand in this study. Price elasticity of water demand is assumed to be equal to -0.35 which is the average of the range reported for residential water demand by Boland et al. (1984). This value matches closely to the -0.33 price elasticity of residential water demand determined by Olmstead et al. (2007). Because this study is concerned with the long-term impact of the price of water on consumption behaviour of water users, only price induced reduction in water demand due to installation of water conserving appliances and plumbing fixtures is considered. It is also assumed that the price induced reduction in water demand occurs over a 10-year demand adjustment period. The limit to which water demand can drop due to price increases is 200 lpcd. This minimum limit is set in accordance with the data published in Environment Canada (2006).

4.3.2 Unit costs of pipe rehabilitation

Younis (2010) reports unit costs of rehabilitation of \$1000 and \$700 per metre for ICG 5 and 4 pipes, respectively. In this study the unit costs of rehabilitating ICG 5 and 4 pipes are assumed to be \$1000 and \$600, respectively. It should be noted that these unit costs do not account for differences in pipe diameters and site specific conditions such as depth, ground conditions and location. Nonetheless, the use of these unit costs is deemed reasonable for the evaluation of long-term management strategies.

4.3.3 Maintenance costs

Maintenance costs are divided into fixed costs and variable costs. Each cost is described in detail in this section.

Fixed maintenance costs include administrative overheads, office supplies, salaries, and benefit costs. These costs are assumed to be constant for a given length of the wastewater network. The fixed component of unit maintenance cost, UM_f (dollars per metre per year), is calculated using Equation 4.1:

$$UM_f = \frac{FC_N}{TL_N \times 1000} \tag{4.1}$$

where FC_N (dollars per year) is the annual fixed cost of managing the network having a total length TL_N (kilometres). TL_N is the sum of all pipe lengths L_g (kilometres) in each internal condition grade g as shown in Equation 4.2:

$$TL_N = \sum_{g=1}^{5} L_g \tag{4.2}$$

Available data from a local utility indicates that fixed maintenance costs (FC_N) are \$2.2 million per year for a 341 kilometres long (TL_N) pipe network. Using Equation 4.1, the fixed component of unit maintenance cost (UM_f) is calculated as \$6.45 per metre per year.

Variable maintenance costs include expenditures on routine maintenance, pipe flushing, and emergency repairs. Utility data with a similar profile of pipes as shown in Figure 4.1 indicates that the annual variable costs for the whole network (VC_N) is about \$1.06 million annually. VC_N is the sum of annual variable maintenance costs for pipes in all internal condition grades as shown in Equation 4.3:

$$VC_N = \sum_{g=1}^{5} VC_g = \$1.06\, million\, per\, year \tag{4.3}$$

where VC_g is the annual variable cost for all pipes in internal condition grade g.

When VC_g is known then the respective variable component of unit maintenance cost UM_{v_g} (dollars per metre per year) for pipes in internal condition grade g can be calculated using Equation 4.4:

$$UM_{v_g} = \frac{VC_g}{\left(L_g \times 1000\right)} \tag{4.4}$$

Utility data was found to be insufficient to determine the annual variable maintenance costs (VC_g) for pipes in different internal condition grades. It is therefore assumed that the variable unit maintenance cost (UM_{v_g}) for pipes in each internal condition grade increases as a geometric series. This assumption is deemed reasonable considering that the underlying structural defect scores associated with internal condition grades also increase geometrically (WRc, 2001). The assumed geometric series is expressed mathematically using Equation 4.5:

$$UM_{v_g} = \left(1 + \frac{\beta}{100}\right) UM_{v_{g-1}} \quad \text{for } g = 2{,}3{,}4 \text{ and } 5 \tag{4.5}$$

where g is the internal condition grade of the pipes and $\beta(\%)$ is the growth rate in variable unit maintenance cost with increasing internal condition grade.

Total unit maintenance cost UM_g (dollars per metre per year) for a pipe in an internal condition grade g is determined by the summation of fixed and variable unit maintenance costs (Equation 4.6).

$$UM_g = UM_f + UM_{v_g} \tag{4.6}$$

An additional constraint is needed to calculate unit maintenance costs (UM_g). This constraint is introduced by comparing the values of UM_g determined using Equations 4.1to 4.6 with the unit maintenance cost determined using the methodology presented in Burnside (2005). Burnside (2005) suggests that annual maintenance cost for a wastewater pipe is equal to 1% of its replacement value. This implies that for a unit rehabilitation cost of $1000 per metre for ICG 5 pipes as assumed in this study (Section 4.3.2), the unit maintenance cost should be $10 per metre per year. It should be noted that Burnside (2005) implicitly assumes that the annual maintenance cost for a pipe remains constant over its life cycle. As previously noted, it is assumed that unit maintenance costs vary with the internal condition grade of a pipe. Therefore, the unit maintenance cost of $10 per metre per year is deemed to be comparable only with unit maintenance cost of pipes in internal condition grade 3 (middle ICG). Using trial and error, it was found that for $\beta = 25\%$ in Equation 4.5, Equations 4.1 to 4.6 yield a value of $9.97 per metre per year for unit maintenance cost of ICG 3 pipes (UM_3). This value is deemed reasonably close to the corresponding value of $10 per metre per year determined using Burnside (2005) methodology. Thus, $\beta = 25\%$ was adopted to determine unit maintenance costs using Equations 4.1 to 4.6 for pipes in all internal condition grades. Table 4.1 summarizes unit maintenance costs for pipes in each ICG.

Table 4.1: Unit maintenance costs for pipes in various internal condition grades.

Description	Unit maintenance cost (dollars/metre/year)				
	ICG 1	ICG 2	ICG 3	ICG 4	ICG 5
Fixed unit maintenance cost (UM_f)	6.45	6.45	6.45	6.45	6.45
Variable unit maintenance cost (UM_{v_g})	2.25	2.81	3.52	4.39	5.49
Total unit maintenance cost (UM_g)	8.70	9.26	9.97*	10.84	11.94

* compares with $10 per metre year determined using Burnside (2005) methodology

4.3.4 Infiltration rate

Figure 4.2 presents monthly volumes of water supplied and wastewater collected by a local utility from 2001 to 2010. This figure shows that wastewater volumes have generally exceeded the volumes of supplied water. On average, the monthly volume of wastewater collected is 25% higher than the corresponding volume of supplied water. At its maximum, monthly wastewater volume has exceeded volume of supplied water by 74%.

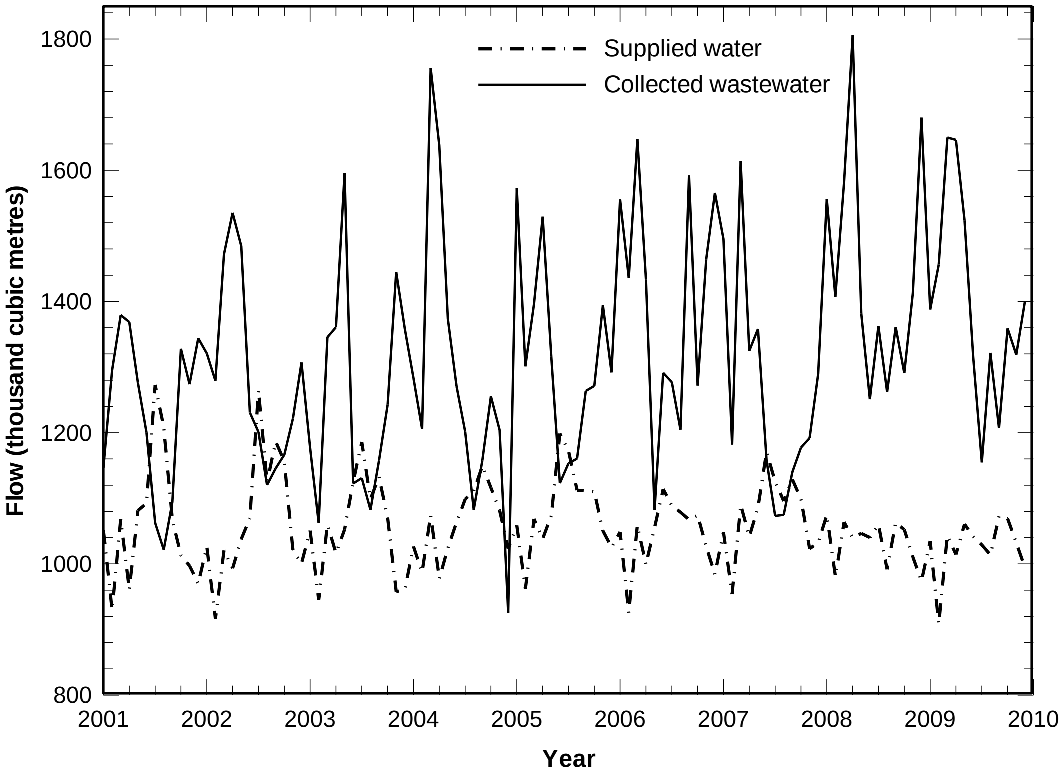


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Figure 4.2: Volumes of water supplied and wastewater collected for a southern Ontario utility.

Figure 4.3 presents the monthly volumes of wastewater collected in excess of supplied water volume, and monthly precipitation from 2001 to 2010. This figure shows that wastewater flows have typically exceeded volumes of supplied water following precipitation events. Precipitation related increases in wastewater flows are due to inflows and/or infiltration. Inflows are caused by direct connection of roof drains and basement sumps to wastewater pipes, leaky maintenance hole covers, and cross-connections with storm sewers. Infiltration is the result of ground water entering the wastewater collection network through pipe defects such as cracks, fractures, holes, and displaced joints. In this study, it is assumed that volumes of wastewater in excess of supplied water volumes are due to infiltration only. Furthermore, because a higher internal condition grade pipe (ICG 4 and 5) has more defects (WRc, 2001), it is hypothesized that the infiltration rate is a function of the pipe's internal condition grade. The daily infiltration rate for the whole network DIR_N (cubic metres per day) is calculated using Equation 4.7:

$$DIR_N = \sum_{g=1}^{5} \left(IR_g \times L_g \right) \tag{4.7}$$

where IR_g and L_g are the average daily infiltration rate (cubic metres per kilometre per day) and length of pipes (kilometres) in internal condition grade g, respectively. Using the average of the excess monthly wastewater flows shown in Figure 4.3 and converting it to daily value, the average daily infiltration rate for the network (DIR_N) is determined to be 8,659 cubic metres per day.

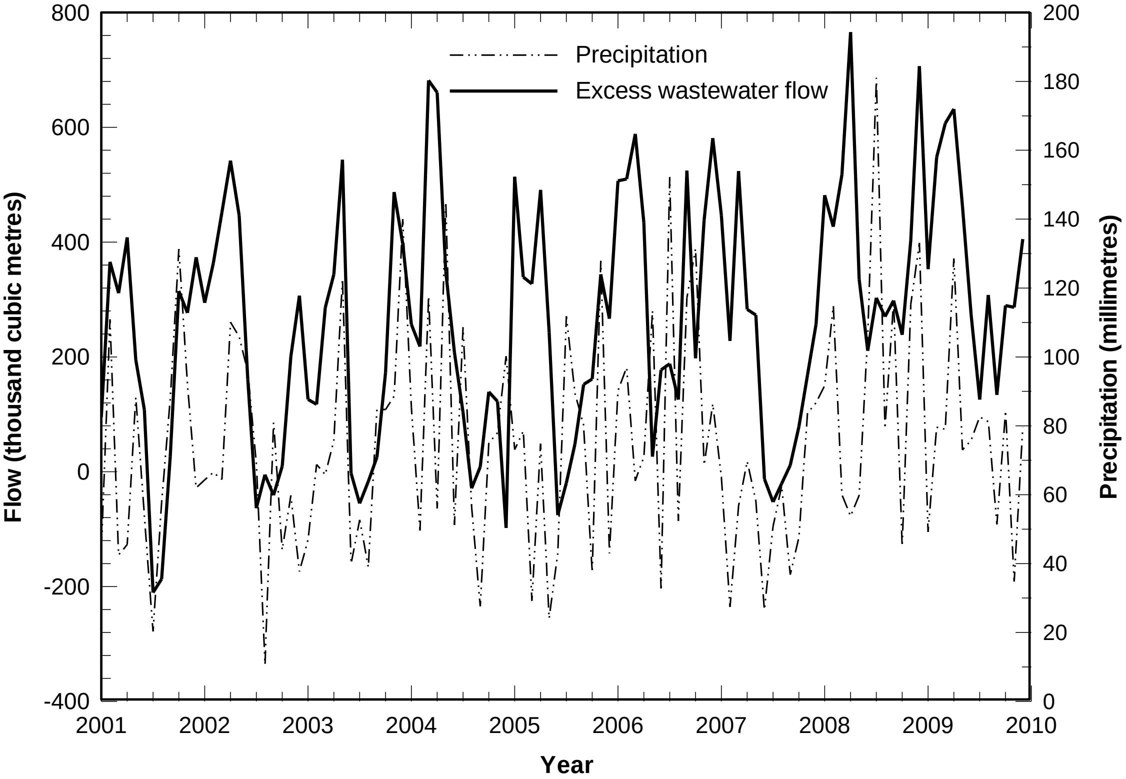


Figure 4.3: Volumes of wastewater collected in excess of supplied water volume and precipitation from 2001 to 2010.

No local water or wastewater utility data is available to correlate infiltration flow volumes with the internal condition grade of pipes. However, Schulz et al. (2005) report infiltration volumes for concrete pipes in various condition grades. It should be noted that Schulz et al. (2005) use a condition rating scheme where grade 6 represents the best condition state and grade 1 represents the worst condition state. This is in contrast to the WRc (2001) condition rating system where ICG 1 represents the best condition state and ICG 5 the worst condition state. Figure 4.4 presents the findings of Schulz et al. (2005). This figure shows that:

- pipes in condition grades 5 and 6 (best states) have no extraneous flows and thus zero infiltration volume; and
- extraneous flows increase exponentially with decreasing condition grade. This finding is reasonable since pipe defects allowing infiltration also increase approximately exponentially with decreasing (for rating scheme used by Schulz et al., 2005) condition grades. Specifically, pipes in grade 1, grade 2 and grade 3 respectively have infiltration rates that are 19, 3 and 2.5 times higher than grade 4 pipes.

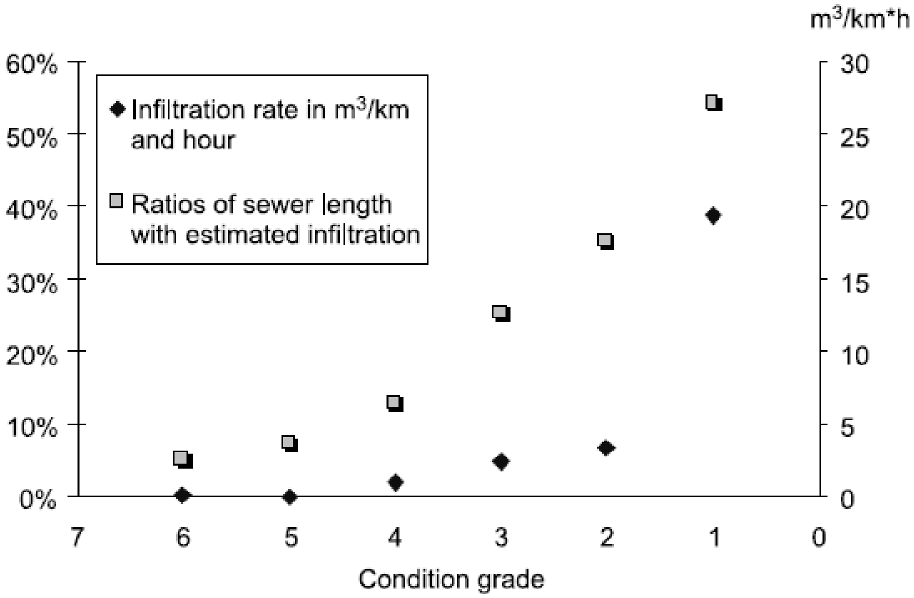


Figure 4.4: Infiltration volumes against condition grades for large concrete pipes (reprinted from Schulz et al, 2005 with permission from the copyright holders, IWA Publishing).

The findings of Schulz et al. (2005) are converted to the WRc (2001) condition rating scheme shown in Table 4.2. Daily infiltration rate IR_g for pipes in each internal condition grade g is determined using Equation 4.7. Table 4.3 summarizes infiltration rates for each internal condition grade.

Table 4.2: Relative infiltration rates for pipes in various condition grades.

Schulze et al. (2005)		WRc (2001)	
Condition Grade	Relative infiltration rate	Condition Grade	Relative infiltration rate
6	0	1	0
5	0	2	0
4	IR_4	3	IR_3
3	$2.5 \times IR_4$	4	$2.5 \times IR_3$
2	$3 \times IR_4$	5	$19 \times IR_3$
1	$19 \times IR_4$		

Table 4.3: Infiltration rates for pipes in all condition grades.

	Internal Condition Grade				
	1	2	3	4	5
Infiltration rate (cubic metres/kilometre/day)	0	0	23	57	435

4.3.5 Average duration of pipes in condition grades

The model requires the average time duration a pipe remains in each internal condition grade before moving to the next worse internal condition grade. For this study, an age-based deterioration model is used. Wirahadikusumah and Abraham (2003) approximate deterioration of pipes as an exponential function in the form of Equation 4.8:

$$Y = e^{\alpha t} \tag{4.8}$$

where Y is the internal condition grade (ICG) of a pipe at age t (years) and α (per year) is a constant for a pipe of given material.

Service life of a pipe is defined as the time elapsed from the pipe's installation at ICG 1 to the time when the pipe reaches ICG 5. When the service life of a pipe is known, Equation 4.8 can be employed to determine α for that pipe material. In this study, a service life of 75 years is assumed for concrete pipes (Younis and Knight, 2010). For PVC and vitrified clay pipes, a service life of 100 years is assumed following the guidelines of the Ministry of the Environment (2007b) and Burnside (2005). For $Y = 5$ and t equal to their respective service life values, α is calculated for concrete, PVC and vitrified clay pipe materials using Equation 4.8.

With α known, the ages at which a pipe attains internal condition grades 2, 3, and 4 are determined using Equation 4.8. Time duration for which a pipe remains in a certain condition grade is calculated as the difference between ages for two successive condition grades. Table 4.4 presents times for pipe in each internal condition grade.

Table 4.4: Average duration of pipes in each internal condition grades.

Material	Service life (years)	α (1/year)	Internal Condition Grade (ICG)				
			1	2	3	4	5
Concrete	75	0.0215	Time (years) from installation to enter ICG				
			0	32.3	51.2	64.6	75
			Time (years) spent in each ICG				
			32.3	18.9	13.4	10.4	N/A*
PVC	100	0.0161	Time (years) from installation to enter ICG				
			0	43.1	68.3	86.1	100
			Time (years) spent in each ICG				
			43.1	25.2	17.8	13.9	N/A*
Vitrified clay	100	0.0161	Time (years) from installation to enter ICG				
			0	43.1	68.3	86.1	100
			Time (years) spent in each ICG				
			43.1	25.2	17.8	13.9	N/A*

* Not applicable

4.3.6 Unit cost of sewage treatment

The current cost of sewage treatment in the Region of Waterloo, Ontario, of $0.65 per cubic metre is used in this study.

4.3.7 Initial sewage fee

As stated in Section 4.2.1, the utility is assumed to be currently replacing 0.85% of its wastewater collection network each year. Using the assumed unit cost of rehabilitation of $1000 per metre for ICG 5 pipes (Section 4.3.2), the current annual capital expenditure is $2.9 million. The initial sewage fee is calculated such that the utility's revenue is sufficient to pay for all operational (sewage treatment and maintenance) and capital expenditures with no surplus (zero fund balance). This calculation results in an initial sewage fee value of $1.26 per cubic metre.

4.4 Model Application to Case Study

4.4.1 Simulation scenarios

The following policy levers are included in the demonstration model:

1. debt capacity of the utility;
2. whether pipes in ICG 4 are rehabilitated;
3. maximum acceptable ICG 5 fraction of pipes in the network;
4. desired elimination period for ICG 5 fraction of pipes in the network;
5. maximum allowable fee hike rate; and
6. preferred network rehabilitation rate.

These policy levers can be used to explore various network management scenarios. Three scenarios are presented in this section to illustrate the trade-offs between issuing debt and adjusting the fee hike rate such that the utility is financially self-sustaining. It should be noted that financial self-sustainability requires that only sewage fee based revenues should be employed to pay for the costs of providing wastewater services. However, this does not preclude using debt as a source of financing capital expenditure as long as the debt plus the associated interest expenditures are ultimately repaid using the utility's own revenues. The scenarios for illustration are chosen such that they have similar total life-cycle costs and pursue the same network rehabilitation rate. However, each scenario involves different debt capacity, and hence the fee hike rate required for financial sustainability is also different under each scenario. Specific values of policy levers adopted for the three scenarios are described below.

The primary difference between the three scenarios is debt capacity. Debt capacity is a policy lever that represents annual debt service charges (principal payment + interest expenses) as a percentage of the utility’s revenues. Scenario 1 involves 0% debt capacity implying that the utility does not borrow at all. This represents the preferred financing strategy of many Canadian municipalities (Kitchen, 2004). Scenarios 2 and 3 have 12.5% and 25% debt capacities, respectively. Thus under Scenario 3, the utility is willing to fully utilize the debt capacity available to it (Ontario, 2003). The debt capacity of 12.5% in Scenario 2 is chosen to represent an equal mix of debt capacities under Scenarios 1 and 3.

Policy levers 2, 3, and 4 are the same for the three scenarios. Subject to availability of cash, pipes in ICG 4 are rehabilitated as a proactive strategy although pipes in ICG 5 still have a higher priority for rehabilitation. Maximum acceptable fraction of ICG 5 pipes is set at 10% of the network. This means that when the fraction of ICG 5 pipes exceeds 10% of the network, the model calculates a new rehabilitation rate (higher than the prevailing rehabilitation rate specified by the user) so that all ICG 5 pipes are then projected to be rehabilitated within a period of 10 years (policy lever 4).

Allowable annual fee hike rates are 3.5%($+r_f$), 0.75%($+r_f$), and 0.25%($+r_f$) for Scenarios 1, 2, and 3 respectively. The preferred network rehabilitation rate is capped at 1.75% per year for all the three scenarios. This rate ensures that the fraction of ICG 5 pipes does not exceed 10% of the network under any scenario. In other words, policy levers 3 and 4 do not (need to) become effective under any scenario. It should be noted that the network rehabilitation rate becomes 0% when all ICG 4 and 5 are rehabilitated. All policy levers for Scenarios 1 to 3 are summarized in Table 4.5.

Table 4.5: Policy levers for Scenarios 1, 2 and 3.

Policy lever	Scenario		
	1	2	3
Debt capacity (Debt service charges as percent of revenue)	0	12.5	25
Rehabilitation of ICG 4 pipes	Allowed	Allowed	Allowed
Maximum acceptable fraction of ICG 5 pipes (% of network)	10	10	10
Desired elimination period of ICG 5 pipes fraction (years)	10	10	10
Maximum allowable fee hike rate (percent per year) ($+r_f$)	3.50	0.75	0.25
Preferred rehabilitation rate (% of network per year)	1.75	1.75	1.75

4.4.2 Simulation results

4.4.2.1 Selected model variables

Behaviour of key model variables for the three scenarios is illustrated over time. The variables are presented according to their respective model sectors (Chapter 3) as follows.

Variables in wastewater collection network sector

Figure 4.5 shows the behaviour of selected variables from the wastewater collection sector of the model. Figures 4.5a and 4.5b respectively illustrate fractions of ICG 5 and ICG 4 pipes as percentage of the total network length. Figure 4.5a shows that for all three scenarios, the fraction of ICG 5 pipes increases from its initial value of 1.5% and after reaching a peak value, eventually decreases to 0.1% by year 35. However, the scenarios differ in terms of peak values attained. Scenario 1 has the highest peak value of 9.5% for ICG 5 pipes fraction while the corresponding peak value for both Scenarios 2 and 3 is 4.5%. Scenario 2 also exhibits a secondary peak value of 3.5%. Figure 4.5b shows that the fraction of ICG 4 pipes starts decreasing from its initial value of 34.3% for all three scenarios and eventually overlaps at a value of 1.1%.

The average internal condition grade of the network (determined using Equation 4.9) is shown in Figure 4.5c for the three scenarios.

$$Average\ Condition\ Grade = \frac{\sum_{g=1}^{5} SwPipeLengths_g \times g}{\sum_{g=1}^{5} SwPipeLengths_g} \tag{4.9}$$

where $SwPipeLengths_g$ represents length of pipes in internal condition grade g.

Average internal condition grade of the network for Scenario 1 initially increases from the starting value of 2.21 to reach a peak value of 2.23 before it starts declining. For both Scenarios 2 and 3, average internal condition grade of the network starts decreasing at the start of the simulation. After reaching its minimum value, average internal condition grade increases for each scenario until the three scenarios converge at 1.73.

Each scenario involves the same preferred rehabilitation rate of 1.75% of the network per year. However, maintaining this rate is subject to availability of cash and whether sufficient pipes in ICG 4 and 5 are available to be rehabilitated. Considering this constraint, it is useful to examine the actual rate of rehabilitation for each scenario as shown in Figure 4.5d. This figure shows that for Scenario 1, the rehabilitation rate starts from an initial value of 0.85% with the preferred rate of 1.75% achieved by year 23. Scenarios 2 and 3 start with the preferred rate of 1.75% from the beginning of the simulation. For Scenario 3, this rate is maintained until year 25. However, in the case of Scenario 2 it decreases suddenly in year 12 before recovering again to the value of 1.75% in year 23. Eventually, the actual rehabilitation rate converges at 1.15% for all three scenarios.

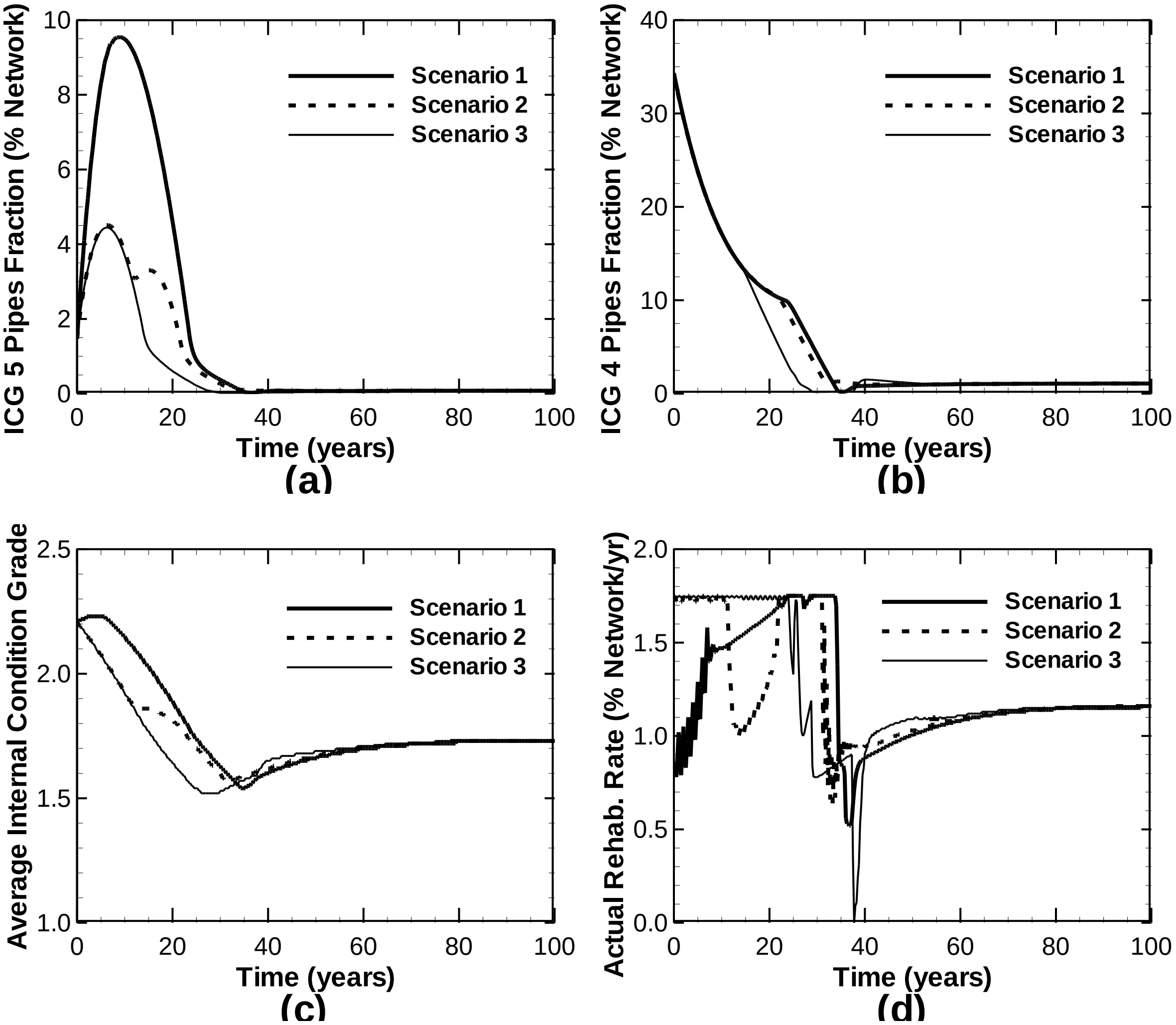


Figure 4.5: Behaviour over time of selected variables from the wastewater collections sector.

Variables in the consumer sector

Two variables from the consumer sector are illustrated in Figure 4.6. The average daily water demand per person is shown in Figure 4.6a. Water demand trends for all scenarios are similar in shape; that is, with an initial period of rapid decrease, followed by a period of no change and finally a declining period again. The main difference is in terms of the initial period where the rate of decline for Scenario 2 is slower than Scenario 1 but faster than Scenario 3. Moreover, the initial period of rapid decline lasts longest for Scenario 3, followed by Scenarios 2 and 1 in that order. Final water demands at year 100 are 267, 267 and 273 litres per capita per day for Scenarios 1, 2 and 3, respectively.

Figure 4.6b shows the total annual volume of sewage for the three scenarios. It is interesting to note that during the first 40 years, total sewage flows for Scenarios 1 and 2 are higher than that of Scenario 3. This is despite the fact that during the same period, water consumption for the former two scenarios is lower than that for Scenario 3 (Figure 4.6a). This is explained with the help of annual infiltration flow volumes. It should be noted that infiltration flow volumes are higher for Scenarios 1 and 2 during the first 40 years and hence are responsible for the higher total flow volumes for these two scenarios during the same period. When infiltration flow volumes for all the three scenarios become equal in year 40, then total sewage volume for Scenario 3 rises above that for the other two scenarios due to higher water consumption under Scenario 3 (Figure 4.6a).

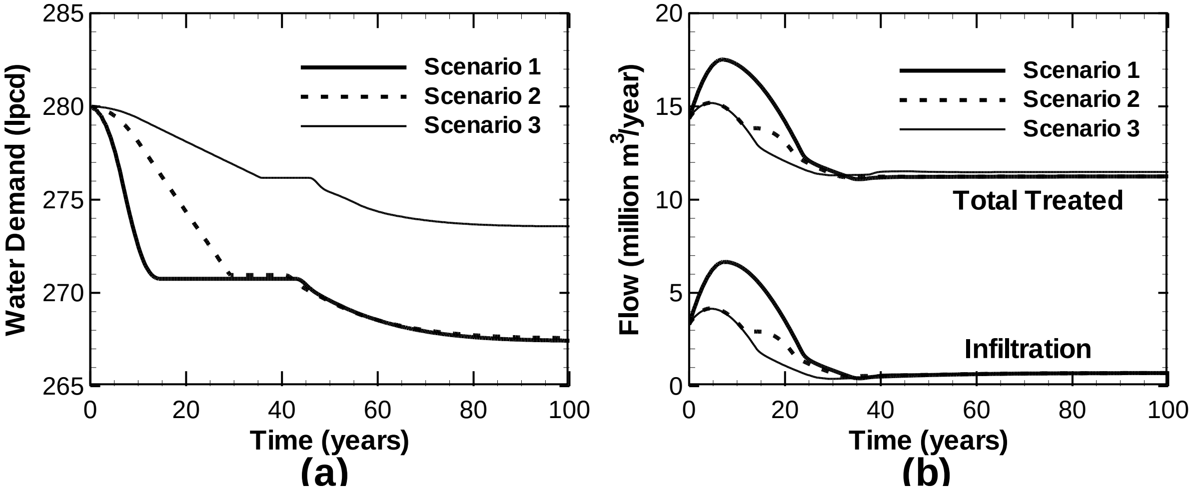


Figure 4.6: Behaviour over time of selected variables from the consumer sector.

Variables in finance sector

Selected variables in the finance sector are illustrated using Figures 4.7 and 4.8.

Figure 4.7a shows the sewage fee trends. Qualitatively the three scenarios show similar trends with an initial period of rapidly increasing sewage fees, followed by a sudden decline and finally a period during which fees continue to climb but at a slowing rate. The three scenarios are markedly different in terms of the initial period of rising sewage fee. It may be recalled that Scenario 1 has the highest allowable fee hike rate followed by Scenarios 2 and 3 in that order. These fee hike rates are reflected in the trends followed by the sewage fee. Scenario 1 exhibits the steepest increase in sewage fee followed by Scenarios 2 and 3 in that order. However, this order is reversed in terms of the time period for which the rising trend of sewage fee persists. Scenarios 3 is then characterized with the longest initial period of rising sewage fee (35 years), followed by Scenario 2 (29 years) and Scenario 1 (8 years). Peak values attained by sewage fee are \$1.62/m^3, \$1.56/m^3, and \$1.38/m^3 for Scenarios 1, 2 and 3, respectively.

The utility's annual revenues are shown in Figure 4.7b. Since revenues are collected on the basis of sewage fee charged to the customers, revenues (Figure 4.7b) essentially follow the same trends as the sewage fees (Figure 4.7a).

Total expenditures incurred by the utility have three components: operational expenditures, capital expenditures and interest expenditures. Figure 4.7c shows annual operational expenditures (OpEx) which consist of costs for maintenance of the network and sewage treatment. Capital expenditures (CapEx) represent costs of rehabilitating pipes in ICG 4 and 5 and are illustrated in Figure 4.7d. Results for annual interest charges (InterestEx) paid on outstanding debt are shown in Figure 4.7e. Finally, annual total expenditures are shown in Figure 4.7f. Figures 4.7c to 4.7f show that annual total expenditures are largely driven by operational expenditures while capital expenditures have a smaller contribution. Interest expenditures (Figure 4.7e) basically depend on the amount of accumulated debt which is shown in Figure 4.8.

The difference between annual revenues and annual total expenditures is manifested in the utility's fund balance as shown in Figure 4.8a. For Scenario 1 with 0% debt capacity, a zero fund balance is maintained except for small surpluses during the initial years. Scenarios 2 and 3 allow borrowing (12.5% and 25% debt capacities, respectively) and hence during the years when annual expenditures are greater than the annual revenues, fund balance for both these scenarios shows accumulating deficit. Scenarios 2 and 3 show peak deficits of $32 million (in year 12) and $46 million (in year 18), respectively. In the latter half of the simulation, fund balance is maintained at zero for every scenario indicating that annual expenditures are matched by annual revenues. Annual debt service charges (principal payment + interest expenses) as a percentage of the utility's revenues are shown in Figure 4.8b. Obviously debt service charges under Scenario 1 remain at zero because no debt is acquired. Debt service for Scenario 2 reaches its peak value of 12.5% in year 12 and is maintained at this value for the next 12 years. For Scenario 3, the corresponding peak value (25%) is attained only during a single year (year 25).

Financial performance as measured by total life-cycle cost and service performance of the network as measure by fraction of ICG 5 pipes in the network, are summarized in Table 4.6 for the three scenarios for comparative purposes.

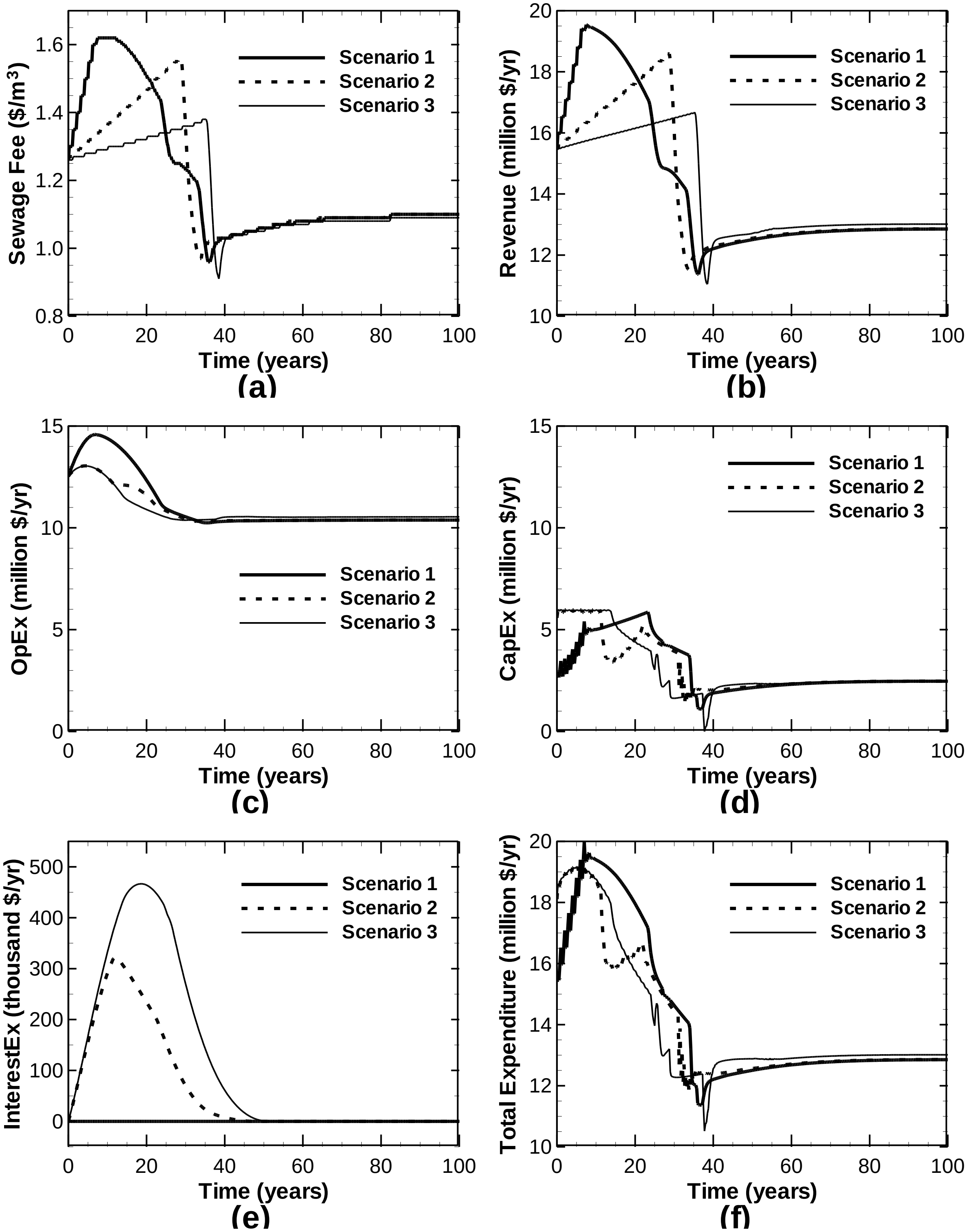


Figure 4.7: Behaviour over time of selected variables from the finance sector-I.

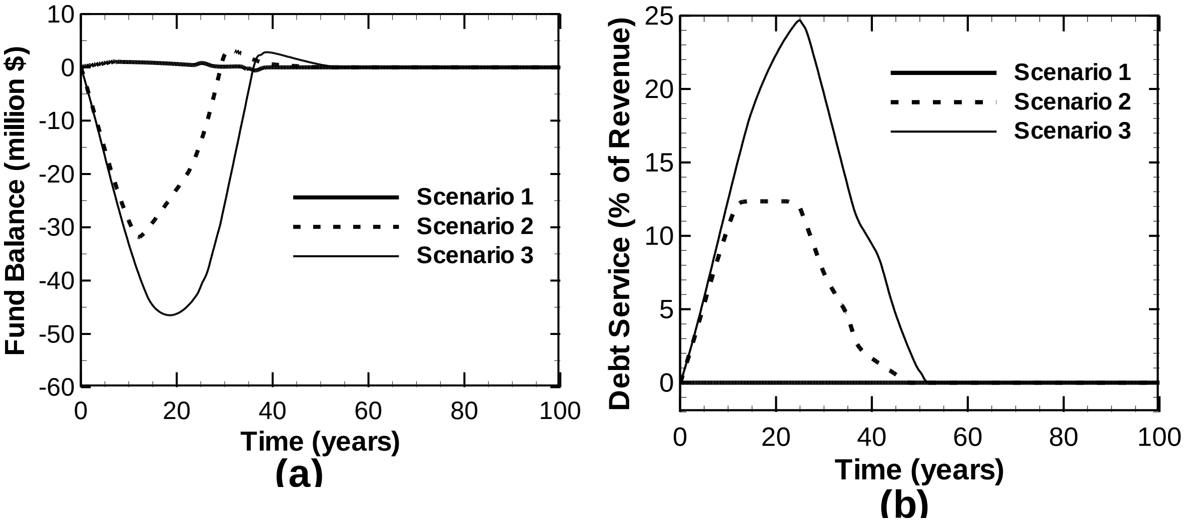


Figure 4.8: Behaviour over time of selected variables from the finance sector-II.

Table 4.6: Summary of results for Scenarios 1, 2 and 3.

		Scenario 1	**Scenario 2**			**Scenario 3**		
	Borrowing Rate $(+r_f)$ (per annum)	**N.A.**	**0.5%**	**1.0%**	**2.0%**	**0.5%**	**1.0%**	**2.0%**
Service Level	Sewage Fee ($/m^3)							
	Maximum	1.62	1.55	1.56	1.64	1.37	1.38	1.41
	Final	1.10	1.10	1.10	1.10	1.09	1.09	1.09
	ICG 5 Pipes Fraction (% of Network)							
	Maximum	9.55	4.51	4.51	7.71	4.45	4.45	4.45
	Final	0.08	0.08	0.08	0.08	0.08	0.08	0.08
	100-year Average	1.71	0.66	0.84	1.82	0.62	0.62	0.92
	Average Network Grade (on scale of 1-5)							
	Maximum	2.23	2.21	2.21	2.21	2.21	2.21	2.21
	Final	1.73	1.73	1.73	1.73	1.73	1.73	1.73
	100-year Average	1.78	1.73	1.75	1.80	1.73	1.72	1.76
Cumulative Life-Cycle Costs	Operational Expenditures							
	(billion $)	1.11	1.08	1.08	1.12	1.09	1.09	1.10
	(% of Total LC)	78.3	77.6	77.4	77.3	77.8	77.4	76.2
	Capital Expenditures							
	(billion $)	0.31	0.31	0.31	0.31	0.30	0.30	0.31
	(% of Total LC)	21.7	22.1	22.1	21.7	21.8	21.7	21.7
	Interest Expenditures							
	(billion $)	0.000	0.003	0.006	0.015	0.005	0.012	0.03
	(% of Total LC)	0.0	0.2	0.4	1.0	0.4	0.8	2.1
	Total LC (billion $)	1.42	1.39	1.40	1.45	1.40	1.40	1.45
Cumulative Operational Costs	Wastewater Treatment							
	(billion $)	0.8	0.76	0.77	0.81	0.77	0.77	0.79
	(% of Total OC)	71.8	70.9	71.1	72.0	71.2	71.2	71.6
	Maintenance							
	(billion $)	0.31	0.31	0.31	0.31	0.31	0.31	0.31
	(% of Total OC)	28.2	29.1	28.9	28.0	28.8	28.7	28.4
	Total OC (billion	1.11	1.08	1.08	1.12	1.09	1.09	1.10
Cumulative Wastewater Treatment Costs	Infiltration							
	(billion $)	0.11	0.07	0.08	0.12	0.07	0.07	0.09
	(% of Total TC.)	14.0	9.6	10.5	14.7	9.2	9.2	11.0
	Sanitary Sewage							
	(billion $)	0.69	0.69	0.69	0.69	0.7	0.7	0.7
	(% of Total TC)	86.0	90.4	89.5	85.3	90.8	90.8	89.0
	Total TC (billion	0.8	0.76	0.77	0.81	0.77	0.77	0.79

LC: life cycle costs, OC: operational costs, TC: treatment costs.

4.4.2.2 Discussion

Figures 4.5a and 4.5c presented service performance of the network as measured by fraction of ICG 5 pipes in the network and average internal condition grade of the network. All three scenarios started with the same initial values of ICG 5 pipes fraction and average internal condition grade. However, over the next 40 years, these service level metrics deviate as the large initial backlog of ICG 4 pipes degrades to ICG 5. This deviation is due to the fact that for the first 22 years, the actual rehabilitation rate for Scenario 1 (Figure 4.5d) is less than the preferred rehabilitation rate of 1.75% of the network per year. While for both Scenarios 2 and 3, the preferred rehabilitation rate of 1.75% per year is achieved at the outset. The lower early-time rehabilitation rate for Scenario 1 results in a peak value of 9.5% of the network being in ICG 5. In contrast, Scenarios 2 and 3 exhibit a peak value of 4.5% of the network being in ICG 5. Despite this large difference in peak ICG 5 fraction values, the average condition internal grade of the network is only a subdued reflection of the same trends. This is due to the fact that the average internal condition grade reflects pipes in all internal condition grades (see Equation 4.9), rather than just those in internal condition grade 5. In summary, the fraction of the network in internal condition grade 5 is a better indicator of the network service performance than the average internal condition grade.

It should also be noted that aside from the differences in peak values of ICG 5 pipe fraction, the three scenarios also differ in the time duration for which the ICG 5 pipe fraction persists. When averaged over the entire simulation period, consumers experience service levels where 1.71% of the network pipes are in ICG 5 every year under Scenario 1. For Scenarios 2 and 3, this figure drops to 0.84% and 0.62% per year, respectively (Table 4.6).

Cash for capital expenditures, as reflected by the actual rehabilitation rate, is generated by two means. First, the sewage fee charged against the consumed water creates a stream of revenue (Figure 4.7b) into the utility's fund. Second, the utility can issue long-term debentures resulting in a negative fund balance. In the case of Scenario 1, the utility is averse to issuing debt and all cash is generated through the sewage fee-based revenue only. To increase revenue required to complete capital work projects, the sewage fee is increased at the maximum allowable rate of 3.5% $(+r_f)$ for the first 8 years. This creates a slight surplus in the fund balance (Figure 4.7d) which then allows the sewage fee to decrease until year 35 even though the rehabilitation rate increases to the capped value of 1.75% of the network/year. A central tenet to making Scenario 1 feasible, is for the utility's customers to tolerate the ICG 5 fraction increasing from 1.5% of the network to a peak value of 9.5% (Figure 4.5a) while seeing large increases in their sewage charges (Figure 4.7a).

Scenarios 2 and 3 involve the utility issuing debt to provide the funds required to maintain network rehabilitation at its targeted value of 1.75% per year. For Scenario 2, the actual rehabilitation rate drops below 1.75% (Figure 4.5d) once the debt service ceiling of 12.5% is reached in year 12. But the growing revenue during this period (Figure 4.7b) makes it possible that more debt is issued without breaching the capped threshold of debt service capacity. This progressive increase in debt allows the actual rehabilitation rate to recover towards the target value of 1.75% by year 23. For Scenario 3, debt service reaches its peak value of 25% in year 25. Unlike Scenario 2, the rehabilitation rate is maintained at 1.75% per year. This is made possible by a combination of three factors: 1) revenues steadily, albeit slowly, increase (Figure 4.7b) until year 35; 2) operational (Figure 4.7c) and interest expenditures (Figure 4.7e) achieve peak values, then embark on a decreasing trend; and 3) capital expenditures decline even though rehabilitation rate is maintained at 1.75% (an issue to be further elaborated below). Thus, even when debt service under Scenario 3 reaches its allowable limit of 25% in year 25, cash is still available to sustain the rehabilitation rate because of the larger revenue stream, lesser competing demand on cash for operational and interest expenditures, and reduced need for capital expenditures. In summary, an increase in borrowing as measured by debt service as a percent of revenue facilitates a longer period during which the preferred rehabilitation rate can be sustained. This is particularly true when a large initial backlog of ICG 4 pipes requires immediate attention as for this particular case study.

Inspection of operational expenditures (Figure 4.7c) shows that these mimic the ICG 5 fraction (Figure 4.5a) and the average internal condition grade of the network (Figure 4.5c). This is not surprising given that the components of operational expenditures (specifically maintenance costs and contribution of infiltration towards treatment costs) are formulated as functions of internal condition grade of pipes in the network (see Sections 4.3.3and 4.3.4). Given that Scenario 1 exhibits the largest ICG 5 fraction as a percent of the network, it also exhibits the highest operational expenditures. Capital expenditures should mimic the actual rehabilitation rate (Figure 4.5d) given that capital expenditures are directly proportional to the lengths of pipes rehabilitated. However, it should be noted that for Scenario 1 during the years 25-35 the rehabilitation rate is maintained at 1.75% of the network/year (Figure 4.5d) while capital expenditures during the same period show a downward trend (Figure 4.7d). This indicates that the pipes rehabilitated during the years 25-35 include an increasing share of ICG 4 pipes as the ICG 5 fraction is effectively removed (Figure 4.5a). Beyond year 35, rehabilitation is focused only on ICG 4 pipes. This permits the utility’s initial capital works expenditure of $3 million/year to decline to $2.5 million/year by the end of the simulation, while the rehabilitation rate of pipes increases from 0.85% to 1.2% of the network/year. These desirable long term objectives are also achieved in Scenarios 2 and 3, albeit with substantially different early-time operational and capital expenditures.

Interest expenditures on debt are shown in Figure 4.7e. Given that the rate of borrowing is only 1% above the risk free rate, peak interest expenditures only reach $450,000/year for Scenario 3 in year 20. In contrast, operational and capital expenditures peak at $15 million/year and $6 million/year, respectively, within the first 35 years when all the rehabilitation activity is required to clear the initial backlog of ICG 4 pipes. Clearly, annual interest expenses on the debt are not substantial relative to the operational and capital expenditures. The reader is reminded that Scenarios 1, 2 and 3 are chosen in part on the basis that they all have nearly identical total cumulative expenditures over the 100-year simulation period. These are summarized in Table 4.6 which shows cumulative life-cycle expenditures of $1.42, $1.40 and $1.40 billion for Scenarios 1, 2 and 3, respectively. In the next section, sensitivity of cumulative expenditures to the borrowing rate is explored.

Consumers' adjustment of their water demand is based on sewage fee and the price elasticity of demand. Scenario 1 shows that as the sewage fee is increased significantly early in time (Figure 4.7a), consumers respond by reducing demand (Figure 4.6a). However, despite the reduced demand and hence billable water consumption, revenue still increases (Figure 4.7b). This is due to the fact that a unit increase in the sewage fee causes less than a unit decrease in water demand and hence the product of billable water consumption and sewage fee results in larger revenue (although less than the amount if price elasticity was assumed zero). Scenarios 2 and 3 also show the same effect to a lesser extent.

Contribution of infiltration to total sewage flows (Figure 4.6b) is greater for Scenario 1 than Scenarios 2 and 3 given that infiltration increases as internal condition grade of the pipes rises. By year 10 Scenario 1 shows that consumers' demand decreases by 3.2% (280 to 271 lpcd) while at the same time the total sewage flow requiring treatment increases by 28.6% (14 to 18 million m^3/year). This increase in sewage volume is due to infiltration. Increased sewage flow results in increased treatment costs which are passed on to the consumers.

4.4.3 Effect of debt capacity on financial and service performance

The three scenarios discussed in the previous section involved different debt capacities. Moreover, each scenario had a unique set of allowable fee hike and preferred network rehabilitation rates. To gain further insights regarding the impact of debt capacity on financial and service performance levels, it is instructive to explore network management strategies over a broader range of allowable fee hike and network rehabilitation rates. This is accomplished by creating three scenario sets corresponding to debt capacity values of 0%, 12.5%, and 25%. Within each scenario set, both allowable fee hike rate and preferred network rehabilitation rate is varied over a range of 0% to 5% per annum. It is assumed that allowable fee hike rate in excess of 5% per annum ($+r_f$) is not a politically feasible strategy for the utility to sustain over the long run. Similarly, a capital works plan rehabilitating in excess of 5% of the network per year is assumed difficult to contractually manage in terms of the utility's administrative resources, apart from issues of labour supply from available contractors to actually bid on and complete such works. Maximum acceptable fraction of ICG 5 pipes and desired elimination period for ICG 5 pipe fraction (see Section 4.4.1) are set at 10% of the network and 10 years, respectively for all three scenario sets. Policy levers for the three scenario sets are summarized in Table 4.7. In this section, results for financial and service performance for the three scenario sets are presented. Financial performance of a network management strategy is indicated by the total life-cycle cost accumulated over the entire simulation period. While the peak value attained by fraction of ICG 5 pipes in the network at any time during the simulation is used as an indicator for service performance.

Table 4.7: Policy levers for three scenario sets.

Policy Lever	Scenario Set 1	Scenario Set 2	Scenario Set 3
Debt capacity (Debt service charges as percent of revenue)	0	12.5	25
Rehabilitation of ICG 4 pipes	Allowed	Allowed	Allowed
Maximum acceptable fraction of ICG 5 pipes (% of	10	10	10
Desired elimination period of ICG 5 pipes fraction (years)	10	10	10
Maximum allowable fee hike rate (percent per year) ($+r_f$)	0 to 5	0 to 5	0 to 5
Preferred rehabilitation rate (% of network per year)	0 to 5	0 to 5	0 to 5

Figures 4.9a, 4.9b and 4.9c present the contours of total life-cycle cost for Scenario sets 1, 2, and 3 with 0%, 12.5% and 25% debt capacities, respectively. For comparative purposes, Scenarios 1, 2 and 3 as discussed in the previous section are illustrated as white dots on Figures 4.9a, 4.9b and 4.9c, respectively. Figures 4.9d, 4.9e and 4.9f show contours of the peak ICG 5 fraction of the network as

observed during the 100-year simulation period for scenarios with 0%, 12.5% and 25% debt capacities, respectively. Once again, for comparative purposes, Scenarios 1, 2 and 3 are depicted with white dots on Figures 4.9d, 4.9e and 4.9f, respectively.

Figures 4.9a to 4.9c indicate that the total life-cycle cost for operating the network decreases as either the allowable fee hike rate or rehabilitation rate increases to its maximum value. The least-cost region tends to be flat for debt capacities of 0%, 12.5% and 25%. From a political and administrative perspective, it appears feasible for the utility to operate near the $1.4 billion contour as suggested by the original choice of Scenarios 1, 2 and 3 (Section 4.4.2). While this is not the least total life-cycle cost, this contour does present minimum values of the combination of allowable fee hike rate and rehabilitation rate. Perhaps most important is the observation that as the debt capacity increases from 0% to 12.5% and finally to 25%, the total life-cycle cost decreases for all combinations of allowable fee hike rate and rehabilitation rate.

Figures 4.9d to 4.9f indicate that the peak ICG 5 fraction, as an indicator of service performance, has a similar shape to the total life-cycle cost and decreases as either the allowable fee hike rate or rehabilitation rate increases to its maximum values. The region corresponding to least values of ICG 5 fraction tends to be flat for debt capacities of 0%, 12.5% and 25%, with contours of 5% and 10% of the network being highlighted for comparative purposes to Scenarios 1, 2 and 3 (see Figure 4.5a and Table 4.6). Once again, from a political and administrative perspective, it is suggested that the utility operate near the 10%-of-the-network contour for 0% debt capacity, and the 5%-of-the-network contour for 12.5% and 25% debt capacity as indicated by the original choice of Scenarios 1, 2 and 3. The most important observation is that contours representing the “optimal” combination of allowable fee hike rate and rehabilitation rate in terms of minimizing either the peak ICG 5 fraction (as a service performance indicator) or the total life-cycle cost (as financial performance indicator) have the same shape. In other words, both indicators can be optimized simultaneously by adjusting the two policy levers (fee hike rate and network rehabilitation rate). Another observation is that no combination of allowable fee hike rate and rehabilitation rate with zero debt capacity (i.e. no borrowing) permits the same desirable service performance level of the network as achieved with 12.5% and 25% debt capacity. No borrowing (as demonstrated by Scenario 1 in the previous section) does impose the harsh reality on the consumers of experiencing poor service performance of the network for a short period of time as the initial backlog of ICG 4 pipes is rehabilitated, all the while sewage fees are increased significantly to generate the required revenue for financial self-sustainability.

Having established the shape of the total life-cycle cost function for allowable fee hike rate and network rehabilitation rate, it is now possible to assess the impact of uncertainty in the borrowing rate. In Section 4.4.2, it was observed that interest expenditures (Figure 4.7e) are relatively small compared to operational and capital expenditures (Figures 4.7c and 4.7d). Figures 4.10a and 4.10c show the impact of alternatively halving and doubling the borrowing rate from 1%$(+r_f)$ per annum (Figure 4.10b) to 0.5%$(+r_f)$ and 2%$(+r_f)$ per annum, respectively, with the utility having a 12.5% debt capacity. Figures 4.10d to 4.10f present the corresponding results when the utility uses a 25% debt capacity. Figure 4.10 indicates that there is a slight increase in total life-cycle cost as the borrowing rate increases for all combinations of allowable fee hike rate and rehabilitation rate. This is due to the fact that interest expenditures increase with upward movements in the borrowing rate, but are small relative to operational and capital expenditures.

Table 4.6 itemizes the cumulative total expenditures for Scenarios 1, 2 and 3 as discussed in Section 4.4.2, but for the borrowing rates of 0.5%$(+r_f)$, 1%$(+r_f)$ and 2%$(+r_f)$ per annum. Here, these costs are broken down into operational, capital and interest expenditures. As stated earlier, interest expenditures for Scenarios 2 and 3 are always significantly less than operational and capital expenditures, even as the borrowing rate rises to 2%$(+r_f)$ per annum. There is a clear trend where issuing debt (Scenarios 2 and 3) causes the cumulative total expenditures to be less than Scenario 1 for a borrowing rate of 0.5%$(+r_f)$ per annum. This trend diminishes as the borrowing rate increases, so that at a borrowing rate of 2%$(+r_f)$ per annum the cumulative total expenditures for Scenarios 2 and 3 are greater than that of Scenario 1. As the borrowing rate increases, interest expenditures also increase causing the utility to spend a greater proportion of revenue on servicing debt. This prevents the utility from rehabilitating the ICG 5 pipes quickly, and then focusing on the ICG 4 pipes (having a lower priority given that they are still serviceable) which are less expensive to rehabilitate. This causes the 100-year average internal condition grade of the network to increase slightly, with a resulting increase in infiltration flows. In summary, operational and capital expenditures increase as the borrowing rate increases. Furthermore, issuing debt is a least total life-cycle cost (and hence better) operational strategy as long as the borrowing rate remains below 2%$(+r_f)$ per annum.

Table 4.6 indicates that as long as the borrowing rate remains below 2%$(+r_f)$ per annum, interest expenditures remain less than the savings in infiltration flow treatment costs. Although many utilities are averse to issuing debt, clearly revenue spent on treating excess infiltration flows is quite literally “money down the drain”. On the other hand, debt financing of capital works stimulates economic activity and creates alternative investment opportunities for financial institutions and is thus beneficial to society at large. It is suggested that for a utility to be truly financial self-sustainable, it should be carefully operated independently of the host city's other municipal activities to protect the credit rating of the utility and facilitate low-interest borrowing. All credit risks associated with the utility should be transparent and directly associated with; (1) engineering uncertainties in managing the network, (2) market fluctuations in the risk free and inflation rates, and (3) the ability of utility customers to pay their bills.

4.5 Conclusions

The following conclusions are drawn from this study:

1. A methodology is presented for parameterization of a system dynamics model that simulates the behaviour of a wastewater collection network management system over a 100-year planning horizon. The model is applied to a case study for exploring alternative management strategies of a utility operating a wastewater collection network. The model enables one to take a holistic view of the system variables within the paradigm of financial self-sustainability.
2. Available utility data is not complete and is missing information crucial for evaluation of network management strategies. Critical data elements that need to be collected and maintained include variable maintenance costs and infiltration rates associated with pipes of different internal condition grades.
3. Results indicate that different management strategies may result in similar total life-cycle costs but with significantly varying impacts on consumers in terms of service level and financial burden.
4. Simulation results indicate that issuing debt, where annual debt service charges reach a maximum of 25% of annual revenues, permit the utility to sustain a capital works program in which a substantial backlog of deteriorated pipes is rehabilitated. This creates a significant improvement in the service performance level of the wastewater collection network compared to when all the expenditures are funded out of sewage fee based revenues. However, the net benefits achieved when the utility issues debt are diminished as the borrowing rate reaches 2% per annum above the risk free rate.
5. Results show that due to interrelationships and feedback loops, model variables influence each other (within and across sectors) in significant ways.

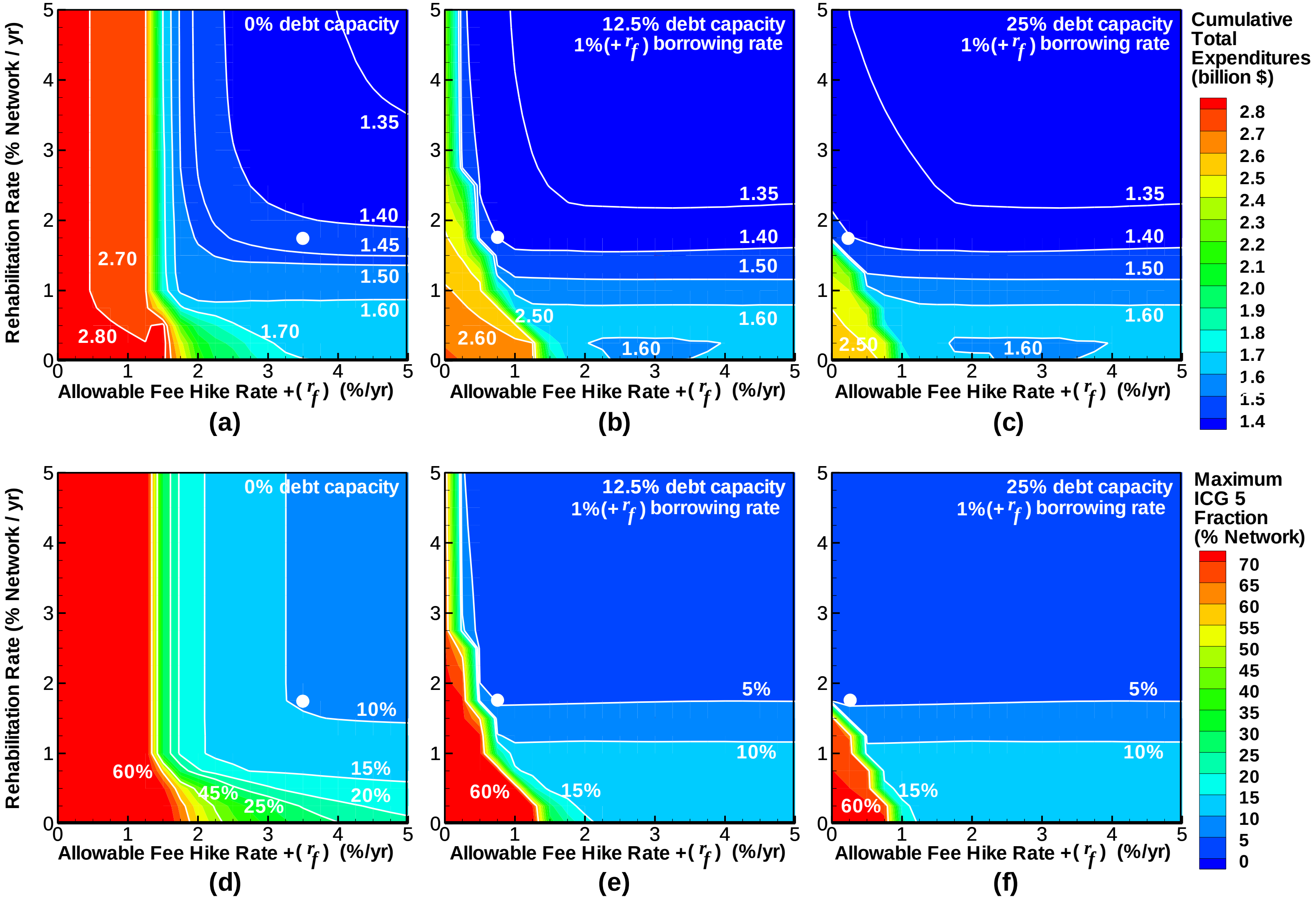


Figure 4.9: Impact of allowable fee hike and rehabilitation rates on total life-cycle cost and peak ICG 5 fraction of the network.

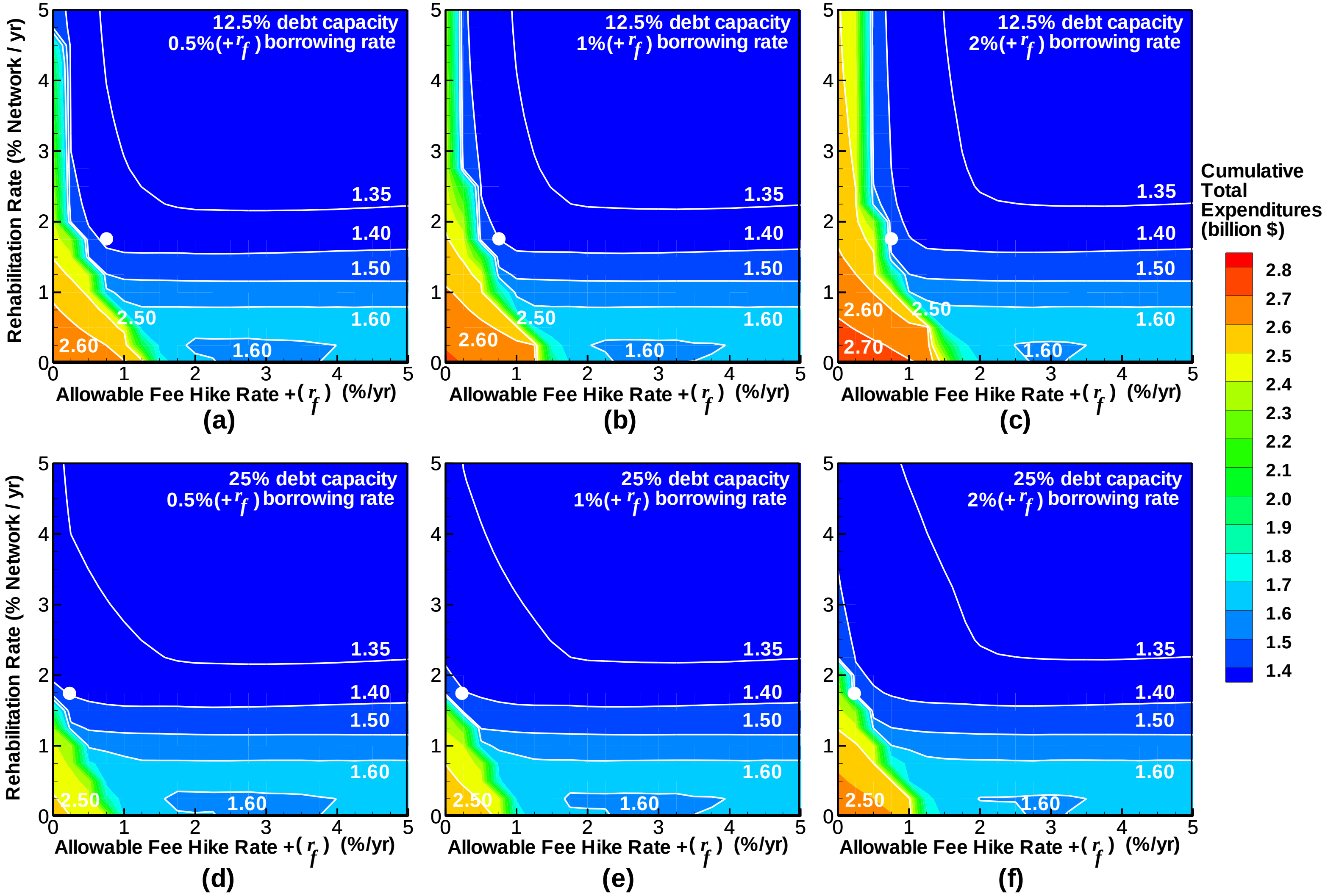


Figure 4.10: Impact of allowable fee hike and rehabilitation rates on total life-cycle cost and peak ICG 5 fraction of the network.

Chapter 5

Financially sustainable management strategies for urban water distribution networks: development of a system dynamics model

5.1 Introduction

Besides being essential for human survival, water supports socio-economic activities which have a direct bearing on the quality of life in human settlements. Water is a primary input in agricultural production and is used in industrial processes such as power generation, manufacturing and mining. Canada is endowed with an abundant supply of freshwater to meet such needs. With only 0.5% of the world's population, Canada has freshwater stocks and renewable water resources that are 20% and 7% of the corresponding world's totals, respectively (Simonovic and Rajasekaram, 2004). At 327 litres per capita per day, Canadian residential consumption is among the largest within the OECD countries (Environment Canada, 2010). The infrastructure installed to satisfy this demand is valued at $32.25 billion (Gagnon et al., 2008).

Perhaps the perception of water abundance can be cited as a reason for the excessive water consumption in Canada. However, a more tangible reason is that the price of water has not reflected the full cost of providing water services (Renzetti, 1999). Swain et al., (2005) indicate that municipal governments utilized grants received from federal and provincial governments to install unnecessary capacity without passing on the cost to customers and that this encouraged overconsumption. Brubaker (2011) states that the expectation of grants motivates municipalities avoid investing their own resources in maintenance of the infrastructure assets. Recently the flow of grants has decreased substantially and is no longer an assured source of funding for municipal governments (El-Diraby et al., 2009). Incidentally, this happens at a time when components of water supply systems, especially pipes constituting the distribution networks, are approaching the end of their service life. The combination of an aging infrastructure, diminished funding resources, and years of neglect in infrastructure maintenance, appears to be a looming crisis (Mirza, 2007). To thwart such a scenario, new legislation and regulations aimed at forcing municipal water utilities to better manage their infrastructure assets, were enacted in Canada during the last decade.

The Canadian Institute of Chartered Accountants Public Sector Accounting Board (PSAB) statement PS3150 requires that all municipalities in Canada, starting in January 2009, report all tangible capital assets along with their depreciation on financial statements (CICA, 2007). In addition, Province of Ontario Regulation 453/07, issued under the authority of the Safe Drinking Water Act 2002, requires that all public utilities prepare and submit yearly reports on the current and estimated future condition of water and wastewater infrastructure (Ministry of the Environment, 2007a). This regulation also requires the preparation and publication of long-term water and wastewater sustainability financial plans. A key principle for these plans is that revenues should be sufficient to pay all expenses of providing services (Ministry of the Environment, 2007b). The most recent piece of legislation, Water Opportunities and Water Conservation Act 2010 (Ministry of the Environment, 2011) goes even further and stipulates the following requirements for municipal water utilities:

- To prepare and submit municipal water sustainability plans for water, wastewater, and storm water services. Such plans are to include an asset management plan for physical infrastructure, a financial plan, a water conservation plan, and a risk assessment and mitigation plan; and
- To report progress towards achieving performance targets in relation to financial, operational and maintenance, and water conservation indicators.

It is argued that the intended goals of above mentioned regulations can only be realized when a holistic view of the water supply systems is adopted within the socio-political context in which these systems function. This implies that water supply systems are treated as complex systems in which physical resources (water, infrastructure) interact with people (consumers, utility management, political decision makers), and capital (financial resources). It is also argued that a change in one of these interacting system components does not remain isolated but effects changes in other parts of the system. Such unintended triggered changes often work against the original policy interventions (Forrester, 1969).

In Rehan et al. (2011), interactions among the physical, social, and financial components of urban water and wastewater networks are illustrated qualitatively using a simplified causal loop diagram. Noting that the demonstration system dynamics model (Rehan et al., 2011) suggests significant implications due to the interacting components, a detailed system dynamics model is developed for management of wastewater collection networks in Chapter 3. The model is then implemented for a hypothetical case study in Chapter 4. In this chapter, a system dynamics model for financially sustainable management of urban water distribution networks is presented. The model is comprised of three sectors namely watermains network, consumer, and finance as shown in Figure 5.1.

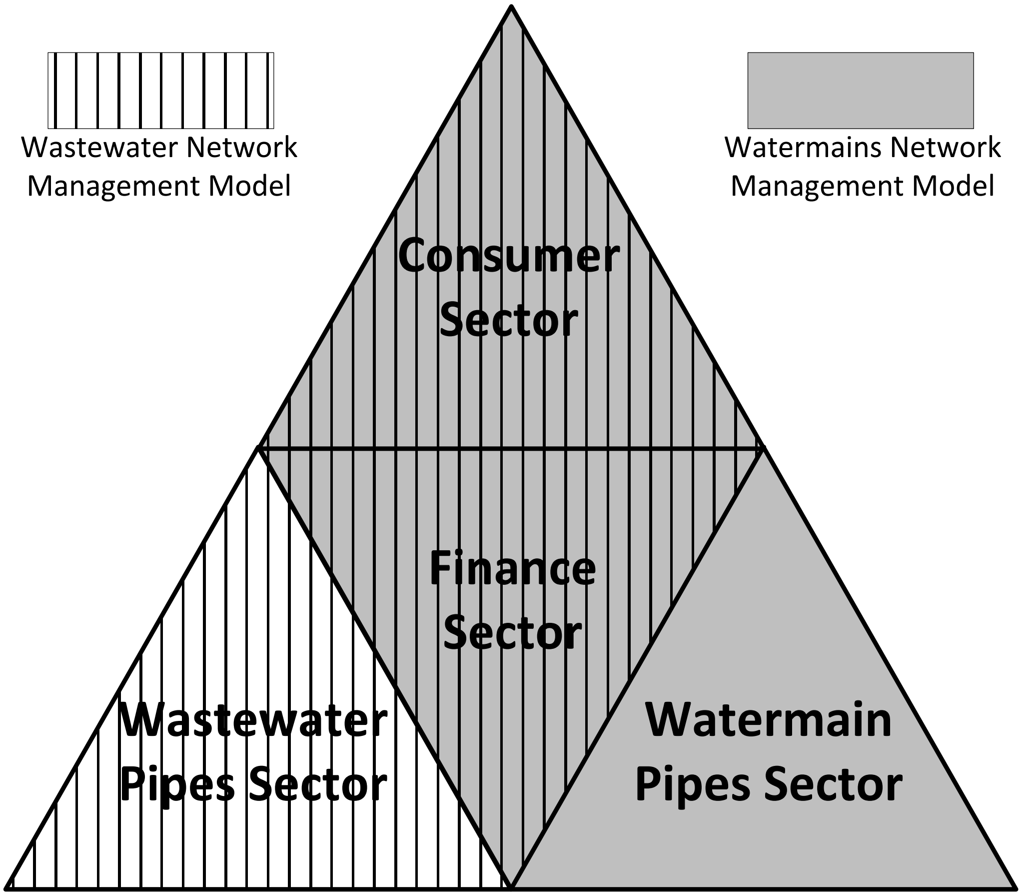


Figure 5.1: Conceptual framework for modelling financially self-sustaining water and wastewater networks.

The objectives of this study include development of a detailed causal loop diagram (CLD) and a system dynamics model for management of water distribution networks. The CLD illustrates qualitative relationships among various system components and identifies feedback loops which are responsible for the complexity of the system. It is the first known CLD for financially self-sustaining water distribution networks. The system dynamics model is a mathematical realization of the CLD that captures dynamic interactions among system variables over time. The model determines all expenditures arising due to various cost drivers involved in the provision of drinking water services. It determines the water fee based on full cost recovery by comparing expenditures with revenues. Several policy levers are provided in the model, these levers enable exploration of different rehabilitation and financing strategies. The strategies can be compared with the help of physical, financial, and customer satisfaction performance indicators.

The following section briefly reviews current literature related to management of water distribution networks. Section 5.3 delineates the scope of this study. A causal loop diagram for the system is presented in Section 5.4. System dynamics model is developed in Section 5.5 and data requirements are discussed in Section 5.6. Conclusions drawn from the research are provided in Section 5.7.

5.2 Literature Review

Current asset management frameworks for water distribution networks involve analysis of watermain pipe data to predict remaining service life; comparison of costs of repair/rehabilitation alternatives over the pipe life cycles; and, prioritization of rehabilitation activities such that available financial resources can be leveraged to achieve maximum benefits (Grigg, 2003).

Rajani and Kleiner (2001) and Kleiner and Rajani (2001) reviewed physically based and statistical models developed for prediction of pipe service life.

A chronological list of various studies suggesting rehabilitation strategies for water distribution networks is provided in Table 5.1. Decision support tools for prioritization of pipe rehabilitation activities can be classified into three broad categories (Englehardt et al., 2000). The first category focuses on individual pipes and aims to determine the optimal time at which a pipe should be rehabilitated. The second category compares candidate pipes for rehabilitation and provides a prioritization scheme within a given budgetary constraint. The third category considers the impact of each pipe on the whole network performance. A rehabilitation strategy is devised such that a given performance goal can be attained at a minimum cost or alternatively performance indicators are optimized for a given budgetary allocation. All rehabilitation strategy models employ a service life prediction model. Starting with the pioneering study of Shamir and Howard (1979), the earlier models belong to the first category that is for individual pipes. Studies belonging to the second and third categories were published about a decade after Shamir and Howard but have recently gained increasing attention.

Table 5.1: Chronological listing of rehabilitation strategy studies for water distribution networks

Reference	**Main Features**
Shamir and Howard (1979) - Individual pipe	Compares present value of costs of repairing pipe breaks with cost of replacement to calculate replacement date
Walski and Pelliccia (1982) - Individual pipe	Develops methodology for a critical break rate and suggests that a pipe needs replacement when its current break rate exceeds the critical break rate
Walski (1987) - Individual pipe	Compares present values of pipe replacement cost and maintenance costs (including break repairs, leaked water cost, leak repair and valve replacement)
Quimpo and Shamsi (1991) – Pipe Prioritization	Prioritizes maintenance decision based on component and network reliability concepts. Reliability measure is the probability that at least one path is open between the source of water and demand point
Lansey et al. (1992) – Optimization	Combines non-linear optimization model with a hydraulic simulation model to minimize costs and while satisfying specified demands and pressure head requirements
Halhal et al. (1997) – Optimization	Genetic algorithm used to optimize rehabilitation decisions subject to funding constraint. Objectives include to minimize costs and maximize benefits (hydraulic capacity, physical integrity, system flexibility, and water quality)
Kleiner et al. (1998a,b) – Optimization	Considers deterioration of both structural integrity and hydraulic capacity of a pipe over time. Proposes methodology to minimize rehabilitation and maintenance costs for the network over a long-term planning horizon
Deb et al (1998) – Pipe Prioritization	System wide prioritization of rehabilitation decisions. Uses cohorts of pipes according to age, material, diameter, and bedding quality. Survival probabilities obtained from Herz probability density function

Table 5.1 continued

Reference	**Main Features**
Kanakoudis and Tolikas (2001) - Individual pipe	Uses Shamir and Howard (1979)'s exponential model to forecast pipe breaks. Calculates replacement time by comparing present values of repair costs with replacement cost. Repair costs also include social costs which are differentiated according to transmission mains and network mains.
Loganathan et al (2002) - Individual pipe	Pipe replacement based on an economically sustainable threshold break rate, when break rate exceeds this threshold then pipe needs to be replaced
Engelhardt et al. (2002) – Optimization	Uses whole life costing methodology. Includes modules for accounting of costs, network definition (structural performance, hydraulic capacity, customer interruptions, leakage, etc), decision tool (investigates impact of interventions such as pipe replacement or leakage control strategy), GA based search technique to determine best maintenance strategies
Burn et al., (2003) – Pipe Prioritization	Based on life-cycle costing. Failure rates for individual pipes modelled as power functions. Intended to include external costs and customer impacts but not implemented
Cheung et al. (2003) – Optimization	Optimization of rehabilitation strategy to minimize costs and satisfy minimum pressure requirements. Using multiobjective Genetic Algorithm and strength Pareto evolutionary algorithm
Saegrov (2005) - Pipe prioritization and optimization	Computer Aided Rehabilitation-Watermains (CARE-W) a comprehensive suite of tools that allow assessment of performance indicators, predict pipe failures, and network reliability. Results generated from these modules are utilized in two further modules that allow for planning long-term investment needs and annual rehabilitation project selection and ranking.
Hong et al. (2006) - Individual pipe	Proposes minimization of annual average costs as an alternative to minimization of total costs over a planning period

Table 5.1 continued

Reference	Main Features
Moglia et al. (2006) – Pipe Prioritization	Includes models for pipe failure prediction, costing customer interruptions, and running scenarios. Explores strategies such as pipe renewal, pressure reduction and shut-off valve insertion
Giustolisi, et al. (2006) - Optimization	Evolutionary polynomial regression for modelling pipe bursts. Multi-objective optimization of investment vs. benefits explored using genetic algorithm search methodology
Dandy and Engelhardt (2006) - Optimization	Trade-off curves between cost and reliability for different replacement decisions. Total number of customer interruptions taken as a measure of reliability. Uses multi-objective GA for optimization.
Berardi, et al. (2008) – Optimization	Uses EPR to predict pipe failure rates, formulated as a multi-objective optimization problem to select pipes with highest risk value
Saldarriaga, et al. (2010) – Optimization	Prioritizes pipes for rehabilitation to achieve two objectives: reduction of water leakage and improving efficiency and reliability of the system (by reducing dissipated energy in the system)
Kleiner et al. (2010) – Optimization	Takes into account economies of scale and coordination of pipe replacements with adjacent infrastructure rehabilitation projects. Minimizes costs for given budget amount. Uses multi-objective genetic algorithm as optimization engine

A review of the works cited in Table 5.1 reveals that currently no decision support tool exists that considers the impact of feedback loops and interconnections between components of water distribution networks, financial and social sectors. Rehan et al. (2011) show the existence of such feedback loops using a causal loop diagram and highlight the significance of feedback loops for financially sustainable management of water and wastewater networks using a demonstration system dynamics model. A growing body of research exists that treats urban water systems as complex dynamic systems whose behaviour is characterized by the underlying feedback loops. Researchers have mainly used the system dynamics (Sterman, 2000) and agent-based (Axelrod, 1997) modelling approaches to study the interactions among various components of urban water systems. A review of relevant literature (provided in Table 5.2) shows that except for Bianchi and Montemaggiore (2008), none of the research in this area addresses management of water distribution networks. Water distribution networks have a critical role in safe and reliable urban water supply and represent the most cost intensive component of urban water supply systems (Ashley and Cashman, 2006). The model presented by Bianchi and Montemaggiore (2008) addresses this issue by incorporating costs related to installation and rehabilitation of watermain pipes. However, the overall model is not based on the principle of financial self-sustainability. As demonstrated by Rehan et al. (2011) and explained further in Section 5.4 below, consideration of financial self-sustainability introduces feedback loops which have significant implications for management of water distribution networks. The current study aims to fill this knowledge gap.

Table 5.2: Complex system approaches to urban water systems

Reference	**Main Features**
Grigg and Bryson (1975)	Studies interactions among population, water supply, and utility's finances. The modelled state variables include: Population, Water Rate, Water in Storage, Water Funds Available, Value of Water System, Water Rights Owned, Debt, and Occupied Land Area
Barton (1994)	Presents a causal loop diagram to explain the social, political, and institutional forces impacting the evolution of a large urban water authority
Palmer et al. (2000)	Use a SD model to study alternatives for water supply and transmission as part of an infrastructure master planning exercise. Insufficient details are provided to assess the underlying assumptions and structure of the developed model
Vo et al. (2002)	Studies impact of urban infrastructure on quality of life in the long-term. Incorporates multi-criteria decision making into SD modelling. Models peoples' dynamic preferences. Groups of actors include: citizens, businesses, and government agencies. Includes 14 sub models: 1) population (and migration), 2) businesses, 3) quality of life, 4) pollution, 5) attractiveness to businesses, 6) attractiveness to individuals, 7) jobs, 8) pollution, 9) cost of living, 10) mobility, 11) road capacity, 12) utilities, 13) utilities capacity, and 14) tax revenue
Chu et al. (2003)	Study development of urban water (and wastewater). Sub-systems include: Municipal water demand, Industry water demand, Urban water supply, Urban wastewater treatment, and Market capacity
Colombo (2004)	Introduces the concept of 'labyrinth' to describe interrelationships and feedback loops related to planning, design, and operation of water distribution systems. The graphic presentation of the labyrinth shows interconnections between Performance, Demand, Capacity, and Total Cost of the system along with their respective underlying drivers

Table 5.2 continued

Reference	**Main Features**
Bagheri and Hjorth (2007a,b)	Present the concept of 'viability loops' which function to check reinforcing feedback mechanisms. They explore the sustainability of an urban water system using causal loop diagrams. Found that the existing management paradigm is missing viability loops
Min et al. (2007)	Analyze interdependency of infrastructure systems. Infrastructure systems including power, petroleum, natural gas, water, and communication are integrated in a system dynamics model such that impacts of localized capacity losses due to disruptions on the whole integrated system are simulated.
Bianchi and Montemaggiore (2008)	The model is not based on financial sustainability because of the political and regulatory environment in which the utility operates. Models four sub-systems: Distribution sector (water treatment and distribution and network rehabilitation), Sewer sector (wastewater treatment), Human resources sector (allocation of auxiliary workers between maintenance and bills collection), and Financial sector)
Chung et al. (2008)	Model subsystems include water sources, users, recharge facilities, and water and wastewater treatment plants. Costs associated with construction, operation and maintenance of infrastructure are calculated. However, do not consider aging and rehabilitation of infrastructure components and associated costs. Detailed modelling of treatment plants, both quantity and quality
Ramirez (2008)	Subsystem include: Users, Rational Choice, Reference Value, Non-Revenue Water, Utility Workers, Normalization, Revenues, and Credit Collection. System dynamics model is used to study effectiveness of water loss reduction programs and policies to reduce non-revenue water

Table 5.2 continued

Reference	**Main Features**
Chu et al. (2009)	Use agent-based modelling to study interactions among regulatory, household and water appliance sectors. Consumers water usage in relation to market penetration of water conserving appliances, regulatory policies, economic development, social consciousness and preferences is studied
Schenk et al. (2009)	Propose a water management model using graphical representation and textual description to identify water issues, their components and interactions.
Ahmad and Prashar (2010)	Studies impact of water conserving appliances, xeriscaping and pricing on municipal water demand. Includes 8 sub-systems: Population, land use, surface water, ground water, municipal water demand, agricultural water demand, environmental water demand, and performance evaluation
Adeniran and Bamiro (2010)	Production, Finance, Operation & Maintenance, and Distribution sectors. Finance sector calculates (capital, operational and maintenance) costs only for the treatment plant. Does not include water distribution and wastewater collection networks
Bianchi (2010)	Presents a SD model to study the dynamics of billing activities, human resources management, company’s finances, and customer satisfaction for a municipal water utility company
Bianchi et al. (2010)	Using causal loop diagram, identify the factors responsible for poor performance of a public water utility and explore intervention policies to ameliorate the situation
Guest et al. (2010)	Use causal loop diagram to explore the sustainability (economic, environmental/ecological, social and function) impacts of wastewater treatment alternatives

Table 5.2 continued

Reference	**Main Features**
El Sawah et al. (2010)	Simulates the dynamics of water supply and demand in response to external drivers such as climate change and population growth. Model sectors include: Catchments module (to represent hydrological processes), Population module (for population growth), Urban Demand module (consumption behaviour in response to climate and demand management measures), Environmental Requirements module (to simulate environmental releases from reservoirs), and Management Policies module (construction of dams, water price increases, education, water use restrictions).
Cheng and Chang (2011)	Use three sub-models to estimate municipal water demand under changing unemployment rate and average income. The sub-models used are Socio-economic, population dynamics and water demand forecast. Effect of price on water demand has not been included.
Wang et al. (2011)	Studies the effectiveness of various supply/demand management options. Specifically they consider interactions between economic development, population growth, water investment, (irrigation, industrial and domestic) water demand, (surface and ground) water supply, water price and water pollution. Found that instead of increasing water supply, demand management instruments and water conservation measures are a sustainable option for the City of Yulin (China) in the long run
Rehan et al. (2011)	Addresses financially sustainable management of urban water and wastewater collection networks. Model includes physical, financial, and social sectors.

5.3 Scope and Limitations

Urban water supply systems are comprised of water abstraction facilities, treatment plants, watermain distribution networks, valve chambers, hydrants, and pumping stations. Of these, watermain pipes represent almost 80% of the life-time costs of the water supply system (Ashley and Cashman, 2006). Energy consumed in pumping along with the associated costs is also a function of the physical condition of pipes (Colombo, 2004). Leakage of treated water from deteriorated pipes is an additional cost burden that undermines achievement of water conservation targets proposed under the Water Opportunities and Water Conservation Act 2010. More importantly, safe and reliable operation of the water supply system hinges upon the condition state of the distribution pipes. Craun and Calderon (2001) and Blackburn et al. (2004) have shown that problems in watermains can cause outbreak of waterborne diseases. Thus, the highest degree of water treatment is rendered meaningless if the treated water is transported through a degraded water distribution network. This study focuses only on watermain pipes. However, the architecture of the developed model allows other physical assets to be easily included in the model such as water treatment plants, hydrants, and valves.

Several Canadian municipalities function as a two-tiered local government. The upper tier municipality typically owns and operates water treatment plant and charges the lower tier for the bulk supplies of treated water. The lower tier municipality owns and operates the water distribution network and collects fees from customers for the provision of water services. Thus, the cost of water treatment is ultimately passed to the customers. Since the owner of water distribution network does not have a control on the water treatment cost, this cost is included as an exogenous variable in the proposed model. Although water treatment cost is not determined within the model, the calculated water fee does reflect the cost of water treatment along with other costs.

Before stating the assumptions made regarding finances of the water utility, a brief discussion of expenditures and revenues for a typical utility in the Province of Ontario is presented. This discussion provides a context to the assumptions stated at the end of this section.

Figure 5.2 provides a schematic overview of the cash flows for the utility. This figure shows that the utility's fund balance is determined by its annual expenditures and annual revenues. The annual total expenditures are broadly classified into capital expenditures ($CapEx$) and operational expenditures ($OpEx$). $CapEx$ is incurred on installation of new and major rehabilitation of existing pipes. $OpEx$ is the sum of water treatment, maintenance, and interest expenditures. Water treatment expenditures are incurred on the total water supply pumped into the distribution network some of which can be lost through leakage. Maintenance expenditures include costs such as salaries, office supplies, equipment, routine maintenance (pipes and hydrant flushing, leak detection) and emergency (unplanned) repairs of burst pipes. Interest expenditures are accrued on the utility's outstanding debt.

Utility's income is typically derived from three sources: development charges, user fee based revenue, and interest earnings. The utility receives one-time development charges from developers to extend water services to new sub-divisions. Fee based revenue is the major and regular source of income which is collected from customers by charging water fee on their consumed (metered) volume of water. Another source of income can be interest earnings that are accrued on utility's cash reserves.

It is assumed that the utility's income does not include grants received from senior (provincial and federal) levels of government. This is partly motivated by the fact that such transfers have been largely discontinued (El-Diraby et al., 2009). More importantly, Regulation 453/07 (Section 5.1) does not allow utility's financial plans to be based on expectations of receiving grants (Ministry of the Environment, 2007b).

Development charges are assumed to be just sufficient to pay for capital expenditures of new construction. Thus, development charges are not used for any other expenditure categories nor are capital expenditures of new construction financed by other sources of income. This means that capital expenditures on new construction and development charges do not impact the calculation of water fees.

It should be noted that financial self-sustainability requires that only revenues collected from provision of water and wastewater services should be used to pay for the costs of these services (Ministry of the Environment, 2007b). Hence financing these services through other sources such as property taxes is not authorized. However, self-sustainability does not preclude using debt as a source of financing capital expenditure as long as the debt plus the associated interest expenditures are ultimately repaid using the utility's own revenues.

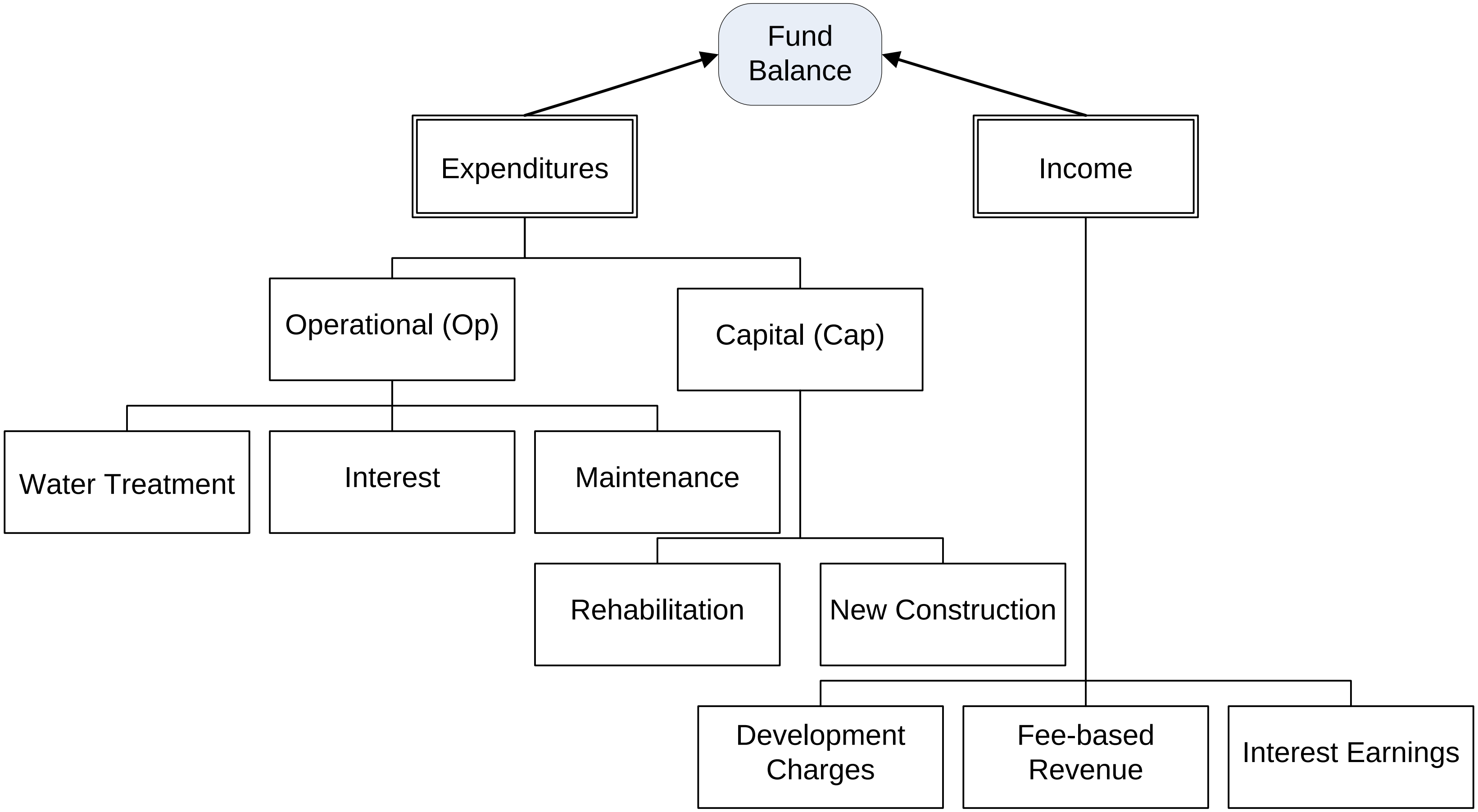


Figure 5.2: Expenditure and income categories for municipal water supply systems in Ontario.

5.4 Causal Loop Diagram for Watermains Network Management

A causal loop diagram (CLD) is a formal tool used to graphically illustrate causal relationships between components of a system. The CLD can be used to identify interactions between system components and feedback loops are formed as a result of such interactions. A feedback loop has causal relationships among system components such that when one component is changed, the perturbation traverses along the loop resulting in a change to the originating component (Hannon and Ruth, 1994). When a change in the originating component causes a change in other components that strengthens the original process, the feedback loop is termed a positive or a self-reinforcing loop. If the response of other components along the loop counteracts the original change, a negative or balancing loop is deemed to exist (Hannon and Ruth, 1994). When a system has multiple interacting feedback loops then it is expected to exhibit complex dynamic behaviour (Sterman, 2000).

In a causal loop diagram, relationships between variables are depicted using arrows with a positive (+) or negative (-) sign placed besides the arrow head to indicate link polarity. A positive link polarity implies that "*if a cause increases, the effect increases above what it would otherwise have been*" and vice versa (Sterman, 2000). Similarly, a negative link polarity "*means that if the cause increases, the effect decreases below what it would otherwise have been*" and vice versa (Sterman, 2000).

A causal loop diagram for management of water distribution network is presented in the following sections. It should be noted that the CLD is presented in three separate parts (Figures 5.3, 5.4 and 5.5). Causal links in these figures are shown using two types of arrows. The ones shown as solid lines imply that such causal links are implemented later in the system dynamics model (Section 5.5). While those shown as dashed lines are included for completeness of the CLD but are not implemented in the system dynamics model because these are beyond the scope of this work.

5.4.1 Feedback loops involving physical condition of watermains network

The discussion in this section includes a variable called network condition. Network condition is defined as collectively representing the physical condition state of all watermain pipes in the network. It is assumed that network condition can be expressed numerically such that higher values represent highly deteriorated state of the pipes and vice versa.

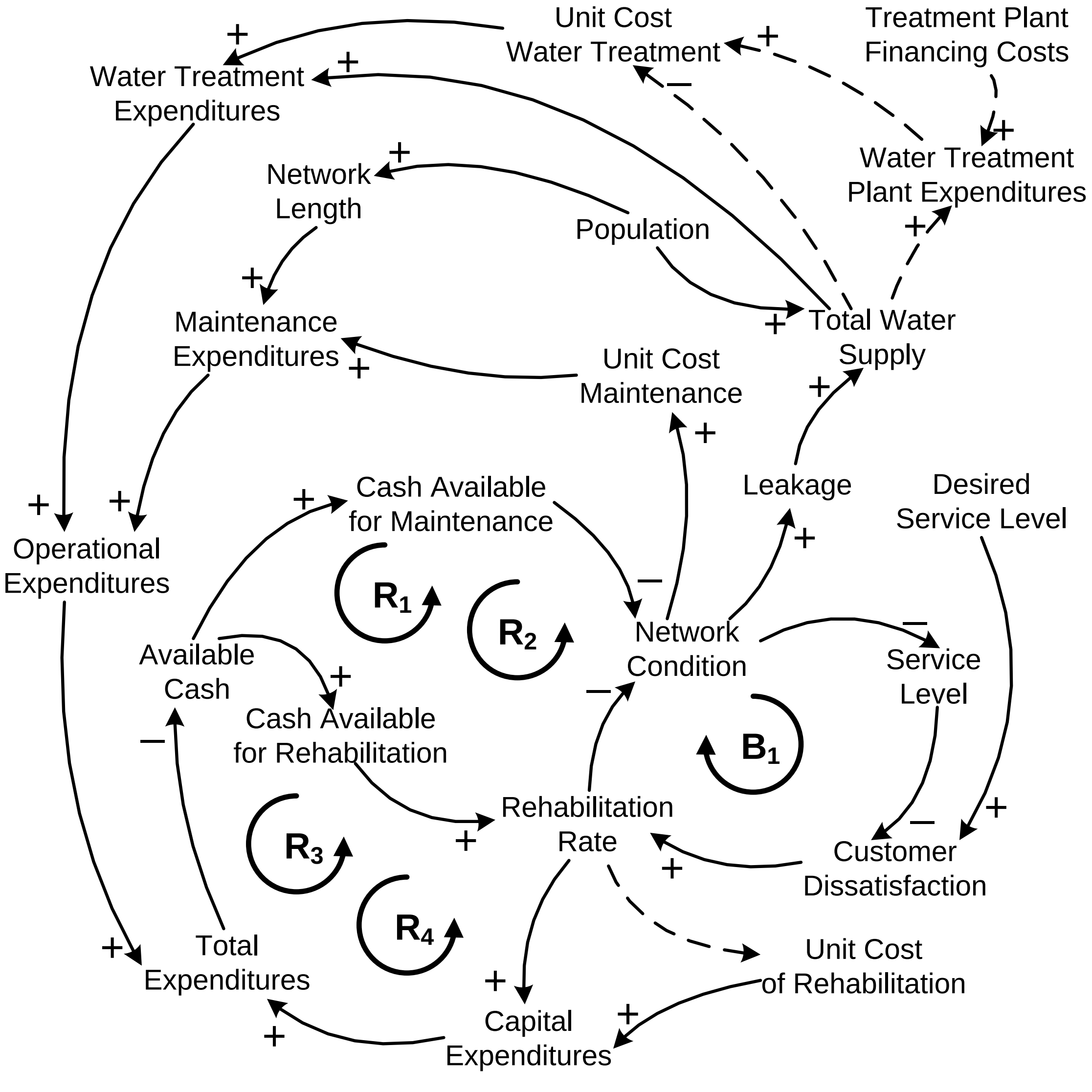


Figure 5.3: Feedback loops involving physical condition of water distribution network.

Figure 5.3 shows feedback loops related to the physical condition of watermain distribution network. This figure shows four reinforcing and one balancing feedback loop involving network condition. Network condition impacts operational expenditures of a water utility through its two component categories that is water treatment and maintenance expenditures. The magnitude of operational expenditures in turn affects network condition by determining the amounts of cash available for maintenance and rehabilitation of the network. These circular causalities give rise to four reinforcing feedback loops, each of which is described as follows.

Reinforcing loop $\mathbf{R_1}$ involves the variables network condition, leakage, water supply volume, water treatment expenditures, operational expenditures, total expenditures, total available cash and cash available for maintenance expenditures (Figure 5.3). Deteriorated pipes lose more water through leakage, whether through continuous background leakage or watermain bursts. Thus, it can be stated that as the network condition increases (pipes deteriorate), leakage increases. Increased leakage means more water has to be pumped into the network to satisfy a given customer demand for water. Higher volume of supplied water implies increased cost on water treatment. Increased water treatment expenditures cause operational and hence total expenditures to increase. Increased expenditures deplete the utility’s available cash. This implies that the utility has less cash left to spend on routine maintenance activities of the network. When routine maintenance such as flushing of pipes, detection and fixing of minor leaks is deferred, it can lead to further deterioration of the network (network condition increases). Thus, an initial increase in network condition ultimately leads to further increase in condition.

Highly deteriorated watermain pipes are associated with higher costs of maintenance. For example, such pipes typically have higher encrustation and are more prone to breaks. Thus, it can be stated that increased network condition causes unit cost of maintenance to increase. Increased unit cost of maintenance means that the same length of network becomes more expensive to maintain and operational expenditures increase. Following the causality from operational expenditures to network condition as described above, the feedback loop, $\mathbf{R_2}$ can be observed.

Similar to their influence on cash availability for maintenance, increased operational expenditures also decrease the cash available to be spent on rehabilitation of the network. A cash crunch impacts the rate at which the utility can rehabilitate the network and this leads to a worse network condition state. Following this causality from operational expenditures to network condition, it can be seen that leakage and unit cost of maintenance form part of two additional reinforcing loops. These are labelled as $\mathbf{R_3}$ and $\mathbf{R_4}$ in Figure 5.3.

It should be noted that the reinforcing loops described above do not have to be interpreted as bringing only bad fortunes to the utility. These feedback loops simply amplify or reinforce a change in one of their component variables. Thus a vicious cycle can be turned into a virtuous cycle for example, if network condition decreases (improves) instead of increasing.

Figure 5.3 shows a balancing feedback loop, $\mathbf{B_1}$, that counteracts the influence of the reinforcing loops. Due to regulatory mandates such as those in place in the United Kingdom (Minister of State, 2008) and the proposed performance targets to be set in Ontario, Canada (Ministry of the Environment, 2011), a water utility is obliged to ensure that its service performance is above some minimum acceptable levels. An increase in network condition means a decrease in the service levels for consumers because deteriorated watermains are responsible for water quality problems (discoloured water events) and disruptions due to watermain breaks. Poor levels of service mean increased customer dissatisfaction. The resulting customer pressure forces the utility to remedy the situation by increasing the network rehabilitation rate provided it has available funds. Thus, deterioration (increase) in network condition, in a functional society, ultimately drives improvement of (decrease in) the network condition.

Figure 5.3also presents a few additional interconnections. These are shown using dashed lines because these are not implemented in the system dynamics model (Section 5.5) but are included for completeness of the causal loop diagram. One set of these relationships involves the unit cost of water treatment. When the total volume of supplied water increases, it impacts the operational and capital expenditures related to the management of water treatment plant. Installation of additional treatment capacity may be necessitated to furnish the increased volumes of water. The associated costs of financing capital expansion are passed on through the unit cost of water treatment. On the other hand, if the existing capacity of the water treatment plant is underutilized then the increased volumes of supplied water imply lower unit costs because water treatment plant expenditures are spread over larger volumes. It is noted that these and other causal relationships related to water treatment plant financing and management are important and may be responsible for interesting dynamic behaviour. However, these require further investigation and are deemed beyond the scope of this study.

Finally, it should be noted that the rehabilitation rate can also influence unit cost of rehabilitation. For example, economies of scale can be achieved by scheduling larger lengths of pipes for rehabilitation. Conversely, a sudden influx of construction projects in a region may overwhelm the delivery capacity of construction firms. The resulting mismatch between the demand and supply drives up the unit cost of construction. Thus, a causal relationship exists between the rehabilitation rate and unit cost of rehabilitation that requires further investigation.

5.4.2 Feedback loop involving consumer behaviour

The way consumers adjust their water consumption behaviour in response to price signals they receive has implications for the finances of water utility (Beecher, 2010). Moreover, public water utilities require the approval of elected officials for any proposed water fee changes (Beecher, 2010; Water Infrastructure Network, 2000). Even in jurisdictions where water supply services are privatized, water fee changes are subject to regulatory oversight. Besides other considerations, the approval process takes into account customer feedback (Falp and Le Masurier, 2009). These considerations point to the existence of three feedback loops shown in Figure 5.4.

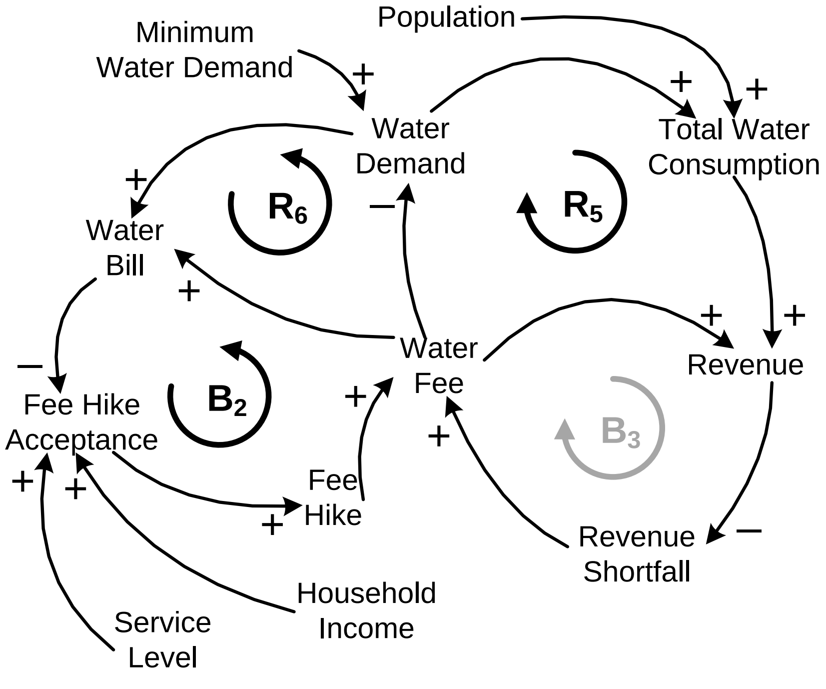


Figure 5.4: Feedback loops involving consumer behaviour.

Water consumption, utility's revenue, water fee, and water demand are interconnected to form a reinforcing loop, shown as **R_5** in Figure 5.4. When the utility's expenditures exceed its revenues then a revenue shortfall grows. To eliminate the revenue shortfall, the utility must increase the water fee.

Consumers can respond to an increase in water fee by reducing water consumption. When revenues are derived on the basis of consumed volume of water then a decrease in water consumption can lower revenues. It should be noted that this self-reinforcing feedback loop may not operate indefinitely as constraints on one or more parameters around the loop can be triggered that stops growth. For instance, once the minimum water demand (due to social or technological limits) is reached, further decreases will not occur regardless of water fee increases.

Reinforcing loop $\mathbf{R_6}$ is comprised of water fee, water demand, water bill, fee hike acceptance, and fee hike. When water demand decreases as a result of an increase in water fee then it means a lower water bill for the customer. A lower water bill implies that customers will be more willing to accept a fee hike. With higher willingness to accept a fee hike, it is more likely that a larger fee hike can be implemented as compared to the situation where willingness to accept hikes is lower. A larger fee hike causes further increase in water fee. Similar to $\mathbf{R_5}$, this feedback loop also becomes ineffective as water demand approaches minimum demand.

Notwithstanding the effect of loop $\mathbf{R_6}$, it should also be noted that demand for water is inelastic (less than -1). This means that for each 1% increase in water fee, the reduction in water demand is less than 1%. This implies that customers cannot fully mitigate the burden of an increased water fee by reducing consumption. Thus, a balancing feedback loop, $\mathbf{B_2}$, exists that counteracts the influence of loops $\mathbf{R_5}$ and $\mathbf{R_6}$.

Household income is included as an exogenous variable that influences the willingness to accept fee hike. Thus, the higher the household income the higher will be the willingness to accept fee hike.

Loops $\mathbf{B_2}$ and $\mathbf{R_6}$ are also connected to loop $\mathbf{B_1}$ through the service level variable. MacDonald et al., (2005); and Rollins et al., (1997) report that consumers are willing to pay positive amounts of money in return for a water supply service that is more reliable and less prone to service interruptions. Since a deteriorated infrastructure system will cause increased service interruptions, it is reasonable to suggest that increased deterioration will increase consumers' willingness to accept a fee hike in return for improvement in the service level.

The balancing feedback loop $\mathbf{B_3}$, shown in gray colour in Figure 5.4 is discussed in the next section in relation to the utility's finances.

5.4.3 Feedback loops involving a utility’s finances

Figure 5.5 shows additional feedback loops which involve a utility’s finances. In this figure, loop **B_3** exists between revenue, revenue shortfall and water fee. As revenue shortfall grows then water fee is increased. A higher water fee implies larger revenue and hence a decrease in the revenue shortfall.

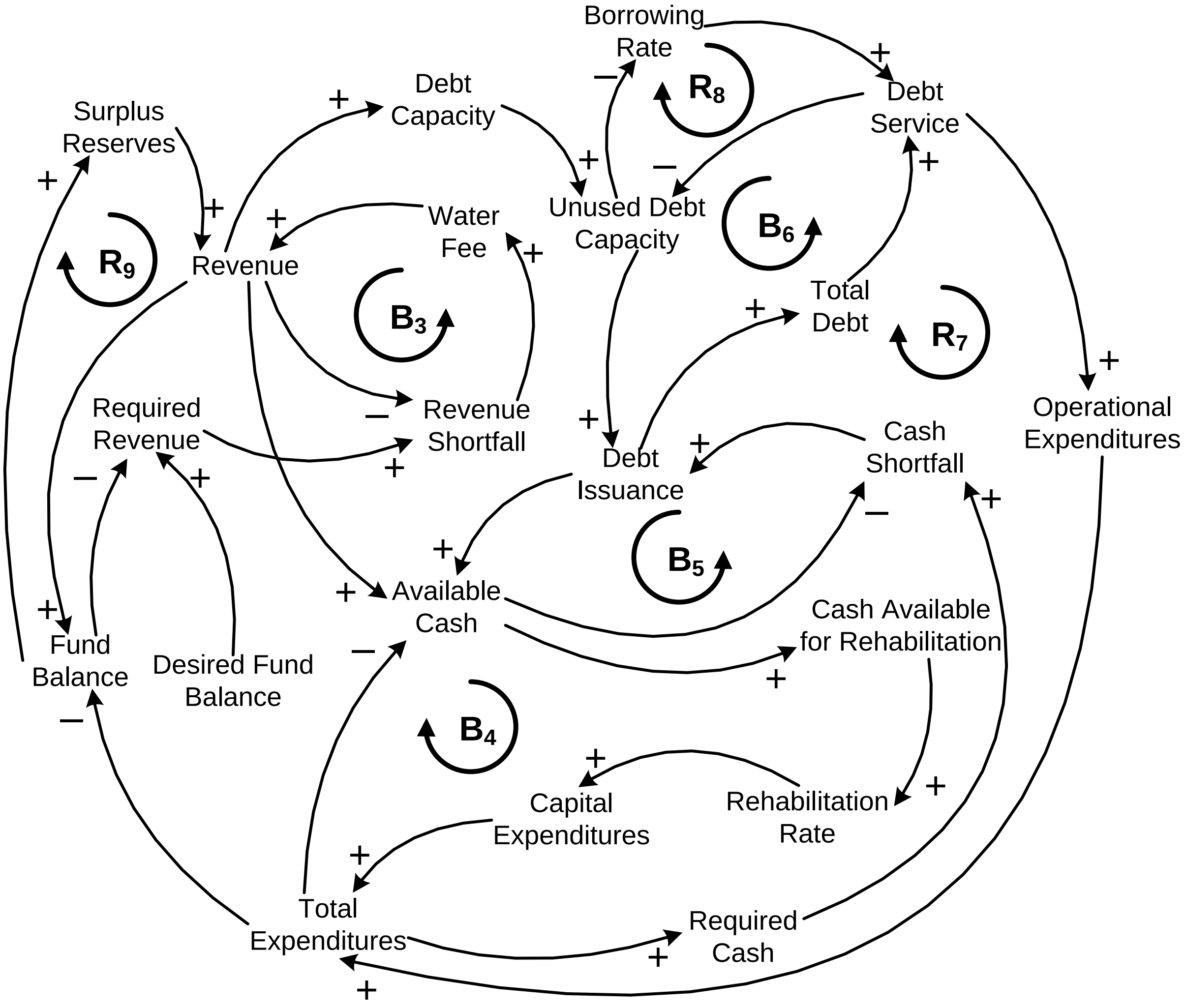


Figure 5.5: Feedbacks involving finances.

Another balancing feedback loop **B_4** is formed due to the interconnection of rehabilitation rate, capital expenditure, total expenditure, available cash, and cash available for rehabilitation. Capital expenditures increase when a utility increases the rehabilitation rate of its network (length of pipes rehabilitated per year is increased). The increase in capital expenditure eventually leads to a lower rehabilitation rate (as explained above in Section 5.4.1). Thus balancing loop $\mathbf{B_2}$ exists.

Cash shortfall, debt issuance and available cash together constitute balancing feedback loop $\mathbf{B_5}$. When the utility's cash shortfall (arising due to a mismatch between available cash and required cash) increases, the utility can issue debt. Debt issuance increases available cash and in turn cash shortfall is reduced.

Water utilities can be constrained in the amount of total debt that they carry through legislative mandates. For example, in the Province of Ontario, Canada, water utilities are restricted from carrying debt that results in annual debt service charges (repayment of principal plus interest) exceeding 25% of annual revenues (Ontario, 2003). Taking this limitation into consideration, debt issuance combines with total debt, debt service, and unused debt capacity to form another balancing feedback loop $\mathbf{B_6}$. This loop implies that increasing debt issuance causes the total debt to grow. An increased total debt means higher annual expenditures on debt service. Increased debt service means that the utility's ability to issue further debt is decreased or its unused debt capacity is reduced. Reduction in unused debt capacity means that further debt issuance is reduced than would be the case otherwise.

Debt issuance also forms part of the reinforcing loop $\mathbf{R_7}$. As stated earlier, higher debt issuance leads to increased debt service. Increased debt service means higher total expenditures. Increased total expenditures imply that utility's cash requirement also rises. This causes the cash shortfall to grow, finally leading to even more debt issuance.

Another reinforcing loop, $\mathbf{R_8}$ exists along unused debt capacity, borrowing rate and debt service. This loop shows that the interest rate at which a utility borrows is a function of its existing debt. If the utility is already carrying a large debt then its debt servicing obligations are high. Higher debt service implies that its unused debt capacity decreases. With a lower unused debt capacity, the utility is able to borrow further only at higher interest rates. Higher borrowing rates imply higher interest expenses thereby increasing debt service charges.

Finally, reinforcing loop $\mathbf{R_9}$ shows the contribution of interest earnings to utility's revenues. When the utility's revenue grows, it leads to a higher fund balance and when revenues exceed expenditures the balance is used to build up utility's reserves. Reserve cash is invested and the interest earned further increases utility's revenues.

5.4.4 Discussion

A causal loop diagram (CLD) for the management a of watermain distribution network is presented in the preceding sections. It is the first known CLD for financially self-sustaining watermain distribution networks. Dell (2005) draws our attention to the problem of organizational silos within water utilities which is caused by individual departments focusing on their own missions and objectives. He suggests that such an organizational structure leads to duplicated effort, loss of efficiency, and difficulty in performance improvement. It is suggested that the causal loop diagrams can be valuable tools in overcoming the 'silo' culture in water utilities. A CLD can be employed to visualize interrelationships that span across departmental boundaries. Thus, the potential consequences of an action can be anticipated (Wolstenholme, 1999). This is especially important when an action originates in one department and its consequences are felt in other department(s). Eventually, the CLD can lead to an improved understanding of the complex challenges facing the utility and the development of a shared vision to tackle those challenges. Hence, even though causal loop diagrams identify causal links only qualitatively, this functionality has value on its own.

The presented causal loop diagram helped identify several interacting feedback loops and thus demonstrates the complexity of managing watermain distribution networks. The influence of these interacting feedback loops can be assessed quantitatively using a formal mathematical model. In the following section such a model is developed using the system dynamics approach.

5.5 System Dynamics Model for Management of Watermain Networks

System dynamics (Forrester, 1958) is a well-established methodology that provides a theoretical framework and concepts for modelling complex systems. It has been applied to a wide range of problems in social and physical sciences (Forrester, 1969; Sterman, 2000; Ford, 1999). Its application to water resource issues include urban scale (examples cited in Table 5.2), watershed/basin scale (Simonovic and Fahmy, 1999; Guo et al., 2001; Tidwell et al., 2004; Ewers, 2005; Simonovic and Ahmad, 2005; Langsdale et al., 2007; Prodanovic and Simonovic, 2006, 2007), multi-basin scale (Simonovic and Rajasekaram, 2004), and global scale (Simonovic, 2002a,b; Davies and Simonovic, 2010,2011). Some examples of system dynamics models for planning and management of infrastructure include electricity market (Ford, 1996; Kilanc and Or, 2008), solid waste management (Sudhir et al., 1997), highways (Fallah-Fini et al., 2010; Hongggang et al., 1998), transportation (Haghani et al., 2010), natural gas (Li et al., 2011),and telecommunications (Shapira, 2004).

The basic building blocks for system dynamics models are; stocks, flows, converters, and connectors (Figure 5.6). Stocks represent accumulations - both physical and non-physical. Examples of physical stocks are inventory of pipes, amount of water in a reservoir, etc. A non-physical stock is the consumer's level of satisfaction with a water utility service. Stocks represent the 'traces' left by an activity. Material in a stock exists at a given point in time and persists even when activities end. Flows represent activities or actions in a stock that transport quantities into or out of a stock instantaneously or over time. Examples of flows are daily consumption of water, monthly revenues and expenditures of a utility, etc.

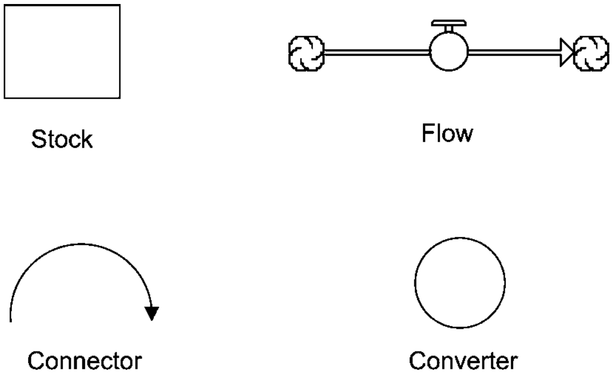


Figure 5.6: Building blocks of system dynamics models.

Mathematically the relationship between stocks and flows can be described using the following integral form (Sterman, 2000):

$$Stock(t) = \int_{t_o}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_o) \qquad (5.1)$$

where t_o is the initial time, t is the current time, $Stock(t_o)$ is the initial value of the stock, $Inflow(s)$ and $Outflow(s)$ are flow rates into and out of a stock at any time s between the initial time t_o and current time t. $Inflow(s)$ and $Outflow(s)$ have the units of $Stock(t)$ divided by time. Connectors (arrows shown in Figure 5.6) establish relationships between various elements of the model and move information as inputs for decisions or actions. Converters house graphical and built-in functions (circles in Figure 5.6). Examples of converters are pipe deterioration curves and demand curves for water usage.

A system dynamics model for strategic management of urban water distribution networks is developed using research version 7.0.2 of Stella® software (Richmond, 2001). The model has three sectors; (1) watermain pipes sector, (2) finance sector, and (3) consumer sector. Salient features of these sectors are described in the following sections. Details of the model including equations for all model objects are provided in Appendix C.

5.5.1 Watermains distribution sector

The watermain distribution sector is shown in Figure 5.7. In this sector, groups of watermain pipes are represented as stocks. Different criteria such as pipe material, age, and diameter can be employed to group the pipes. But the essential requirement is that the classification criteria should result in homogenous pipe groups such that all pipes in a group can be assumed to have similar structural behaviour (Savic, 2009).

Figure 5.7 shows stock-flow structures for cast iron and PVC pipes. Within each structure, individual stocks represent pipes of various age groups for the respective material. For example, stock $CI\ 50\ to\ 74$ represents cast iron pipes from 50 to 74 years old. The categorization scheme presented in Figure 5.7 can be easily extended to include additional pipe materials and other classification criteria.

It is assumed that only PVC pipes are used both for the expansion of the network to serve growing population, as well as, for replacement (rehabilitation) of existing pipes in the network. Inflow $New\ Installation$ represents expansion of the network length and is formulated as a function of growth in population and typical pipe lengths required to serve a unit increase in population.

The ageing process of pipes is represented using flows such as $PVC\ Aging\ to\ 25$. As the pipes contained in stock $PVC\ 0\ to\ 24$ reach the age of 25 years, they are moved to the subsequent stock $PVC\ 50\ to\ 49$. The same function is performed by other aging flows.

It should be noted that only five stocks are provided for cast iron pipes which implies that age distinction is not maintained for cast iron pipes older than 100 years. This is consistent with the industry practice and is based on the assumption that cast iron pipes have a service life of 100 years. Seven stocks are reserved for PVC pipes with the last stock representing pipes older than 150 years. However, it should be noted that the model allows for discarding older pipe stocks simply by setting the inflow feeding a stock to zero. For example, setting the flow $PVC\ Aging\ to\ 125$ to zero effectively makes the stock $PVC\ 100\ to\ 124$ as the last one in the stock chain for PVC pipes. The succeeding stocks then play no role in model simulations. The same is true for cast iron pipes, $CI\ 75\ to\ 99$ can be made the oldest stock in the chain simply by setting $CI\ Aging\ to\ 100$ to zero.

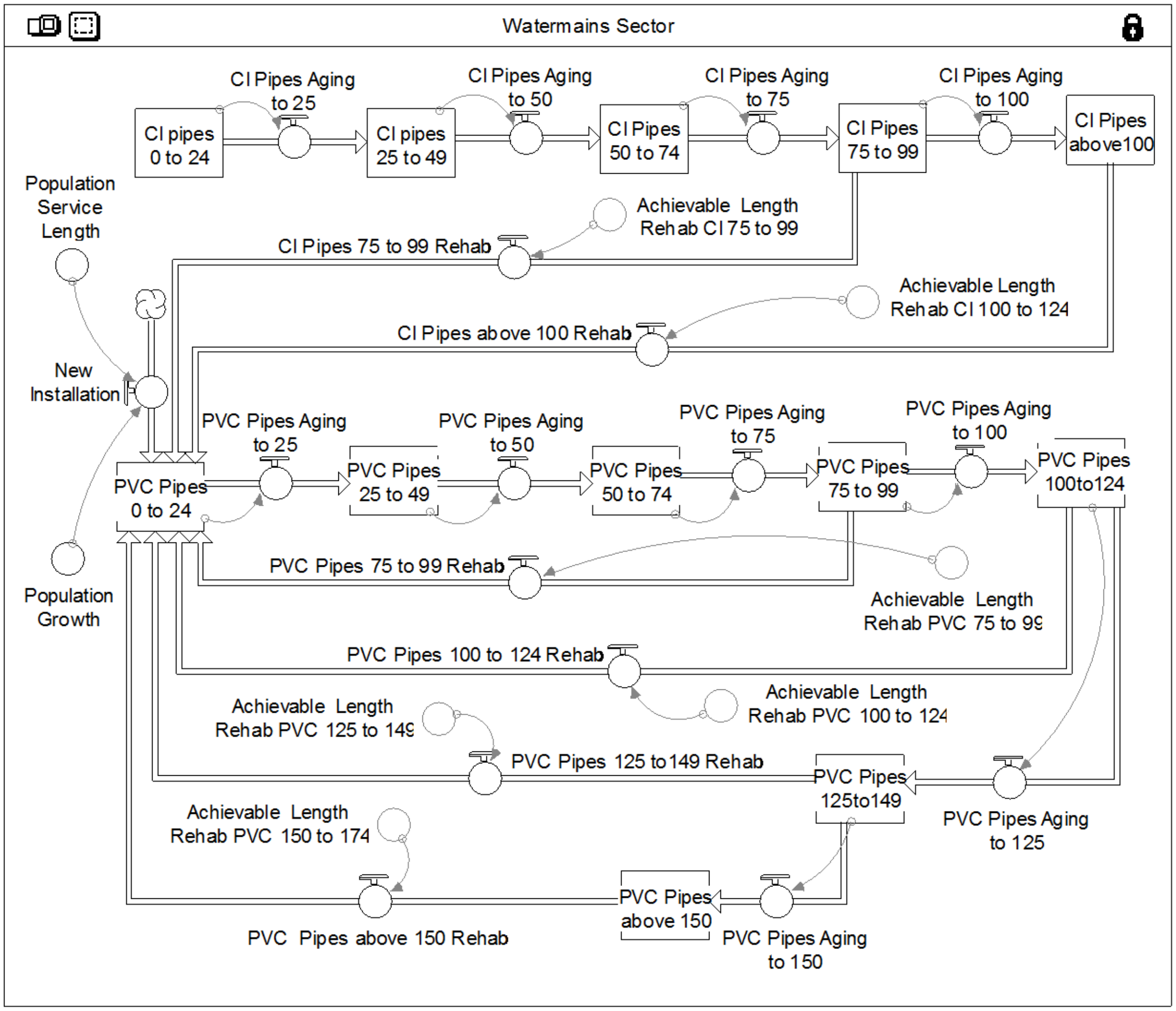


Figure 5.7: Watermain pipes sector of the model in Stella®.

Rehabilitation of older pipes is represented using flows such as $CI\ above\ 100\ Rehab$. This flow moves pipes from stock $CI\ above\ 100$ to stock $PVC\ 0\ to\ 24$. This means that cast iron pipes older than 100 years are replaced with new PVC pipes. Other $Rehab$ flows serve similar a purpose. Though not currently included in the model, it is possible to add flows representing rehabilitation activities other than just replacement of pipes. For example, if a cast iron pipe belonging to age group 75 to 99 years is structurally repaired such that it service life is extended by another 25 years then this rehabilitation activity can be represented using a flow emanating from stock $CI\ 75\ to\ 99$ and terminating at stock $CI\ 50\ to\ 74$.

Lengths of pipes that are moved from various stocks of older pipes to stock $PVC\ 0\ o\ 24$ depend upon the user specified values for policy levers which control how much length of pipes and from which stocks has to be rehabilitated annually. These policy levers are discussed in Section 5.5.4 below. However, here it is noted that regardless of their desired values as controlled through the policy levers, lengths of pipes that are actually rehabilitated are constrained by the availability of cash to perform rehabilitation works. This is implemented in the model using converters such as $Achievable\ Length\ Rehab\ CI\ 75\ to\ 99$. Depending upon the cash available for rehabilitation each year, the model calculates the actual achievable lengths for rehabilitation during that year. When cash availability is a limiting factor, the model gives priority to rehabilitation of older pipes.

This sector also calculates volume of water that leaks from the network due to continuous background leakage or pipe bursts. Following Walski (1987), it is assumed that the volume of water leaking from a pipe of given material depends upon the pipe's age. Hence each pipe stock is assigned a leakage fraction. The leakage fraction of a pipe stock is defined as the percentage of annual water consumption that is lost as leakage when the whole network is comprised of pipes belonging to this particular stock. Mathematically, $Annual\ Leakage$ volume (cubic metres per year) is given by:

$$Annual\ Leakage = Annual\ Water\ Consumption \times \sum_{i=1}^{g} \left(\frac{LF_i}{100} \times \frac{L_i}{L_N}\right) \tag{5.2}$$

where $Annual\ Water\ Consumption$ (Section 5.5.3) is the annual volume of water consumed (cubic metres per year), LF_i and L_i are respectively the leakage fraction (%) and lengths of pipes (kilometres) corresponding to the i^{th} pipe stock, $L_N\left(= \sum_{i=1}^{g} L_i\right)$ is the total length of the network (kilometres), and g is the total number of pipe stocks representing the network.

$Annual\ Leakage$ volume and $Annual\ Water\ Consumption$ together constitute the total annual volume of water purchased which is used in determining $Water\ Purchase\ Ex$ (Section 5.5.2).

The number of watermain breaks is used as an indicator of network's service performance. Pipe material and age information for each pipe stock can be used in statistical models (e.g., Shamir and Howard, 1979; Walski, 1987; Kleiner et al., 1998a; Kanakoudis and Tolikas, 2001) to predict annual number of expected breaks for respective stocks. If the number of breaks associated with a pipe stock exceeds the maximum tolerable number of breaks specified by the user, then such a pipe stock is designated as a highly deteriorated pipe stock. Succeeding older pipe stocks in the same stock-chain then also fall under the highly deteriorated category. The fraction of network that comprises highly deteriorated pipes, PFN_{HD} (% of network) is calculated as follows:

$$PFN_{HD} = \frac{100}{L_N} \sum_{i} L_i \tag{5.3}$$

where L_N is the total length of all pipes in the network (kilometres), and L_i is the length of pipes (kilometres) in stock i such that for all i, the number of breaks, Br_i (number per year) exceeds the maximum tolerable number of breaks, Br_{max} (number per year). Equation 5.3 shows that PFN_{HD} can vary from 0% (no pipe in the network is in highly deteriorated state) to 100% (the whole network is comprised of highly deteriorated pipes. Equations governing this sector are presented in Appendix C.

5.5.2 Finance sector

The finance sector is shown in Figure 5.8 and includes four key variables; fund balance, working capital, debt, and water fee. Each variable has associated stock-flow structures and these structures are connected to other variables.

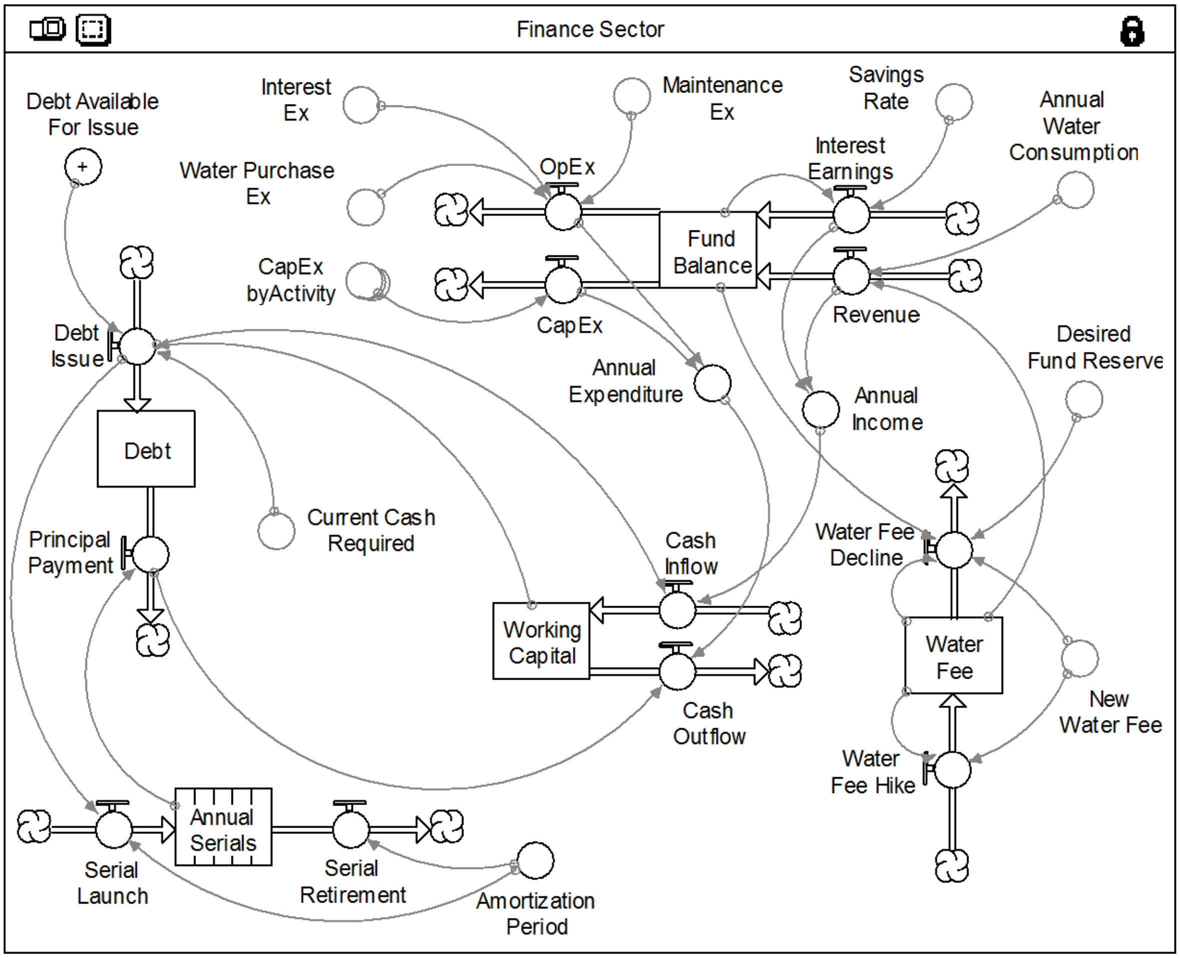


Figure 5.8: Finance sector of the model in Stella®.

5.5.2.1 Fund Balance

Stock *Fund Balance* represents the profit/loss account of the utility and indicates the net surplus or deficit that the utility accumulates over time. The value of *Fund Balance* can fluctuate between positive and negative values, but the objective is to maintain *Fund Balance* at a user defined value. This is accomplished by continuously adjusting *Water Fee* over the course of simulation as described in Section 5.5.2.4. $Fund\ Balance$ has two inflows and two outflows. Inflows represent sources of the utility's income and outflows represent expenditures.

The main source of income is the revenue generated by charging a user $Water\ Fee$ against metered water consumption. The flow $Revenue$ is calculated as a product of stock $Water\ Fee$ and converter $Annual\ Water\ Consumption$. The latter is explained in Section 5.5.3. The other source of income is $Interest\ Earnings$ that is calculated using a user specified $Savings\ Rate$ for positive $Fund\ Balance$ maintained over a simulation time step.

Outflow $CapEx$ is calculated by multiplying length of pipes rehabilitated during a time step with the unit cost of rehabilitation. Outflow $OpEx$ represents the sum of $Water\ Purchase\ Ex$, $Maintenance\ Ex$ and $Interest\ Ex$. $Water\ Purchase\ Ex$ is the product of $Unit\ Cost\ Water\ Treatement$ and the total volume of supplied water (leakage volume plus $Annual\ Water\ Consumption$). $Maintenance\ Ex$ is the sum of annual maintenance costs incurred on all the pipes in the network as shown in Equation 5.4:

$$Maintenance\_Ex = \sum_{i=1}^{g} (UCM_i \times L_i \times 1000) \tag{5.4}$$

where UCM_i (dollars per metre per year) and L_i (kilometres) represent the unit cost of maintenance and length of pipes for the i^{th} pipe stock, respectively and g is the total number of stocks for the whole network.

5.5.2.2 Working Capital

The amount of cash available to the utility is represented by stock $Working\ Capital$. Cash flow into this stock is comprised of the utility's annual income (revenue and interest earnings) and the amount of debt issued during any year. The utility's available cash is spent on operational and capital expenditures (Section 5.5.2.1) and re-payment of the principal portion of outstanding loans. Cash allocations to re-payment of loans and operational expenditures have a higher priority than that for capital expenditures. Hence, capital expenditures can be lower (or even zero) than the planned amounts, depending upon the cash left after debt re-payments and paying for the operational expenditures. When available cash exceeds the cash outflows during an year, then the surplus amount is reserved for future use. It should be noted that stock $Working\ Capital$ cannot be negative while stock $Fund\ Balance$ can be both positive and negative.

5.5.2.3 Debt

The amount of debt carried by the utility is represented by stock $Debt$. At each time step, the amount of cash available and cash reserve is compared with the cash requirement. If cash required is more than the available cash then debt is issued to cover the shortfall. Debt issuance is subject to the constraint of debt capacity imposed upon the utility. This means that new debt can only be issued as long as annual debt service (principal re-payment plus interest charges) does not exceed a specified fraction of the utility's revenue. It is assumed that the utility borrows funds by issuing long-term debentures known as 'straight serials'. Such serials require annual principal payments of equal amounts and are preferred by the municipalities over other types of debentures (Fortin et al., 2002). In the model, when new debt is issued, the required serial for its re-payment is calculated by dividing the amount of issued debt by the $Amortization\ Period$. The value of serial is added to the stock $Annual\ Serials$ which represents the utility's annual obligation for re-payment of the principal portion of all outstanding loans. A serial added to stock $Annual\ Serials$ remains there for the duration of the $Amortization\ Period$ after which it is removed through the outflow $Serial\ Retirement$, signifying that the corresponding loan is fully paid off. The outflow $Principal\ Payment$ reduces the stock $Debt$ by an amount equal to the value of stock $Annual\ Serials$.

5.5.2.4 Water Fee

Stock $Water\ Fee$ tracks the price per unit volume of water charged to the customers. $Required\ Fee$ is calculated such that it generates sufficient revenues to maintain $Fund\ Balance$ at a desired level (see Section 5.5.2.1). When the $Required\ Fee$ is less than the prevailing value of $Water\ Fee$ then the latter is adjusted downward by the difference between the two. Conversely, when $Water\ Fee$ is less than the $Required\ Fee$, then upward adjustment in $Water\ Fee$ is made as follows.

The increase required to make $Water\ Fee$ equal to $Required\ Fee$ is modified by applying two adjustment factors as shown in Equation 5.5.

$$\begin{aligned} &Acceptable\ Fee\ Hike \\ &\quad = Proposed\ Fee\ Hike \\ &\quad \times MIN[Financial\ Burden\ Acceptability/100 \times (1 \\ &\quad + Service\ Level\ Acceptability/100),1] \end{aligned} \tag{5.5}$$

where

$$Proposed\ Fee\ Hike = Required\ Fee - Water\ Fee \tag{5.6}$$

$Financial\ Burden\ Acceptability$ reflects the impact of the water bill's financial burden to the customers. This value ranges from 0% (customers are not willing to accept any fee hike at all) to 100% (consumers are willing to accept full fee hike). The concept of $Service\ Level\ Acceptability$ is based on the hypothesis that customers' willingness to accept fee hikes increases with decreasing levels of service. Its minimum value is 0% which means customers are satisfied with their existing level of service and their willingness to accept fee hike is governed by financial burden considerations alone. The maximum limit of $Service\ Level\ Acceptability$ is 100%. This value implies that the customers are completely dissatisfied with the level of service and their willingness to accept fee hike due to financial considerations alone is doubled. The function $MIN(\quad)$ is used in the right hand side of Equation 5.5, to ensure that the combined effect of $Financial\ Burden\ Acceptability$ and $Service\ Level\ Acceptability$ does not cause an increase in fee above the required $Proposed\ Fee\ Hike$. Formulation of $Financial\ Burden\ Acceptability$ and $Service\ Level\ Acceptability$ are discussed in Section 5.5.3.

Model users can also specify a fee hike rate by which the $Water\ Fee$ is allowed to increase annually as shown in Equation 5.7:

$$Allowable\ Fee\ Ceiling = Water\ Fee \times (1 + Allowable\ Fee\ Hike\ Rate/100) \tag{5.7}$$

such that

$$Allowable\ Fee\ Ceiling \leq Required\ Fee \tag{5.8}$$

It should be noted that regulations in the Province of Ontario require utilities to have sufficient revenues to pay for operational expenditures and annual debt repayment obligations (Kitchen, 2002). $Minimum\ Required\ Fee$ is calculated such that this minimum revenue requirement is met. Thus, the new value assigned to stock $Water\ Fee$ is determined using Equation 5.9.

$$\begin{aligned} &New\ Water\ Fee \\ &\quad = MAX[(Water\ Fee + Acceptable\ Fee\ Hike), \\ &\quad (Allowable\ Fee\ Ceiling), (Minimum\ Required\ Fee)] \end{aligned} \tag{5.9}$$

The above described procedure for adjusting $Water\ Fee$ at every time step is illustrated as a flow chart in Figure 5.9.

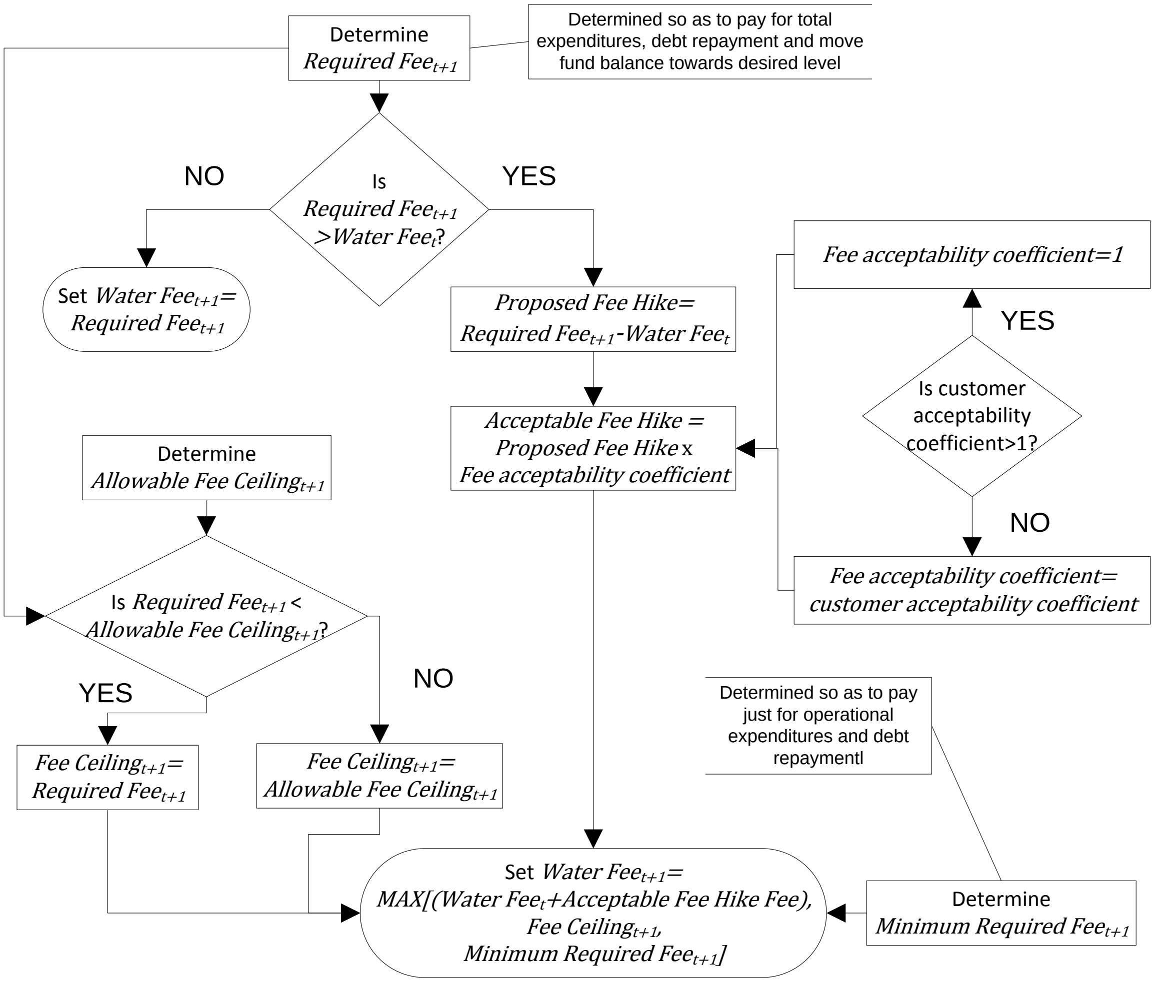


Figure 5.9: Flow chart for updating stock $Water\ Fee$.

5.5.3 Consumer sector

The amount of water consumed is modelled in the consumer sector (Figure 5.10). The daily volume of water consumed per person is determined using stock $Water\ Demand$. This stock can change through its outflow $Price\ Induced\ Reduction$ which is a function of $Price\ Elasticity$ of water demand, $Water\ Fee$, $Minimum\ Water\ Demand$ and $Demand\ Adjustment\ Period$. Lipsey and Chrystal (1999) define price elasticity of demand as the percentage change in a demanded quantity of a good divided by the corresponding percentage change in its price. Thus, stock $Water\ Demand$ is depleted through the flow $Price\ Induced\ Reduction$ as water fee increases. The rationale for the water demand decrease is that customers will implement water conservation measures (i.e. retrofitting of plumbing fixtures and the installation of water conserving appliances) to reduce their water bills as water fees increase. It is also assumed that once water conservation measures are implemented, they are permanent. Therefore, water demand is assumed to remain constant at its minimum attained level even when water fees decrease. Price induced changes in water consumption are not instantaneous and occur over time (Fortin et al, 2002). Therefore, the water demand reduction calculated using the $Price\ Elasticity$ is implemented over a $Demand\ Adjustment\ Period$. The converter $Minimum\ Water\ Demand$ is used to set a minimum water demand limit. Total water consumption is the product of the average per capita water demand and the population served by the utility.

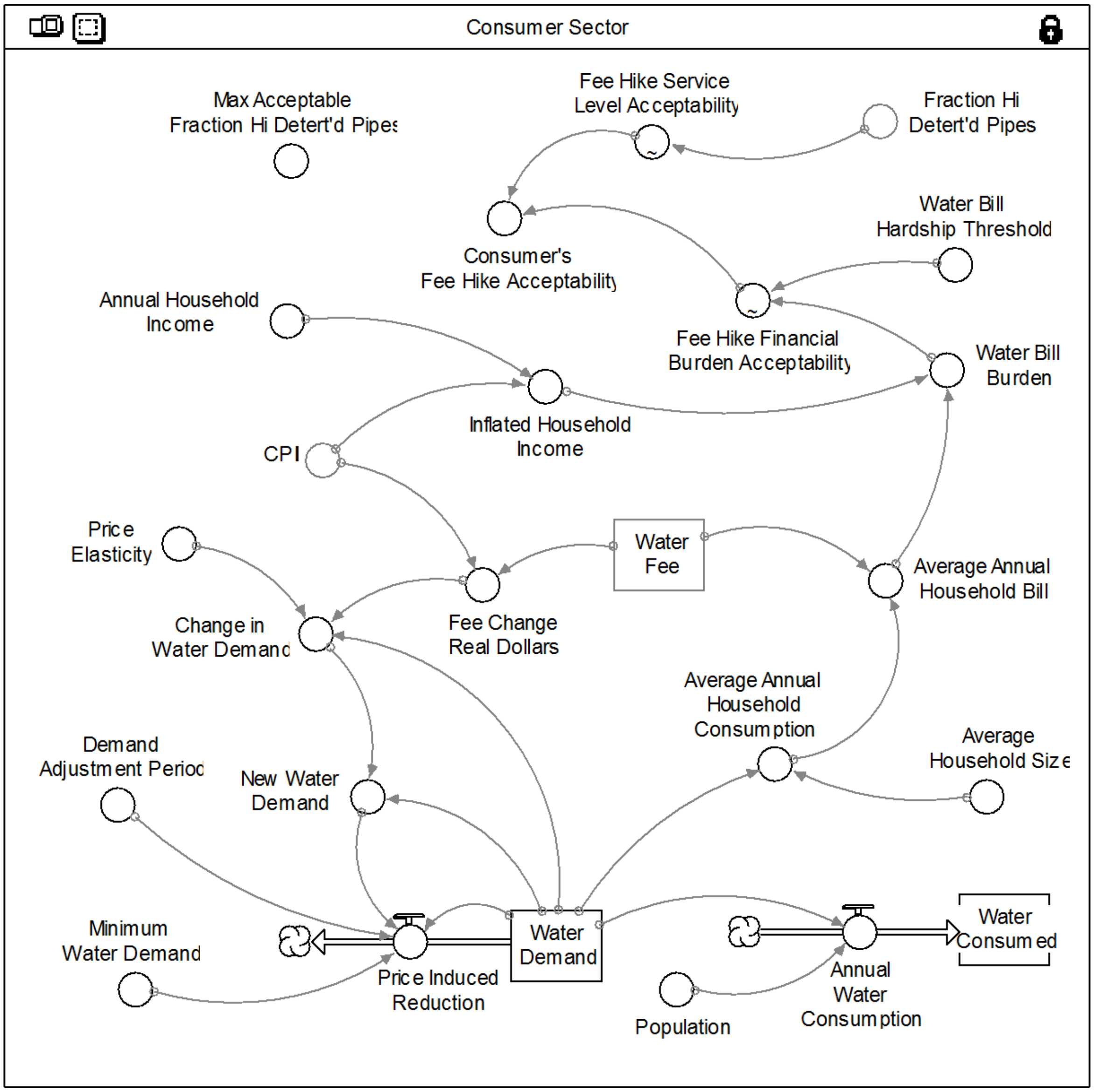


Figure 5.10: Consumer sector of the model in Stella®.

Financial Burden Acceptability and *Service Level Acceptability* (Section 5.5.2.4) are calculated in this sector. According to the US Environmental Protection Agency, a water bill that is more than 2 percent of a household income constitutes a financial hardship (Water Infrastructure Network, 2000). This criterion is used to formulate *Financial Burden Acceptability* in the model. The formulation requires user specified median household income (dollars per year) of utility's customers, and a representative household size (number of persons). The annual average water bill for a typical household is determined using Equation 5.10.

$$Household\ Water\ Bill = Household\ Size \times Water\ Demand \times \frac{365}{1000} \times Water\ Fee \tag{5.10}$$

The annual water bill is expressed as a fraction ($Water\ Bill\ Burden$) of the household income which can be inflated during the simulation using a suitable index such as the consumer price index.

$$Water\ Bill\ Burden = \frac{Household\ Water\ Bill}{Inflated\ Household\ Income} \times 100 \tag{5.11}$$

It is assumed that as the $Water\ Bill\ Burden$ approaches the hardship threshold (EPA's suggested 2 percent or a user specified value) then the $Financial\ Burden\ Acceptability$ quickly diminishes. The shape of this relationship is hypothesized as shown in Figure 5.11.

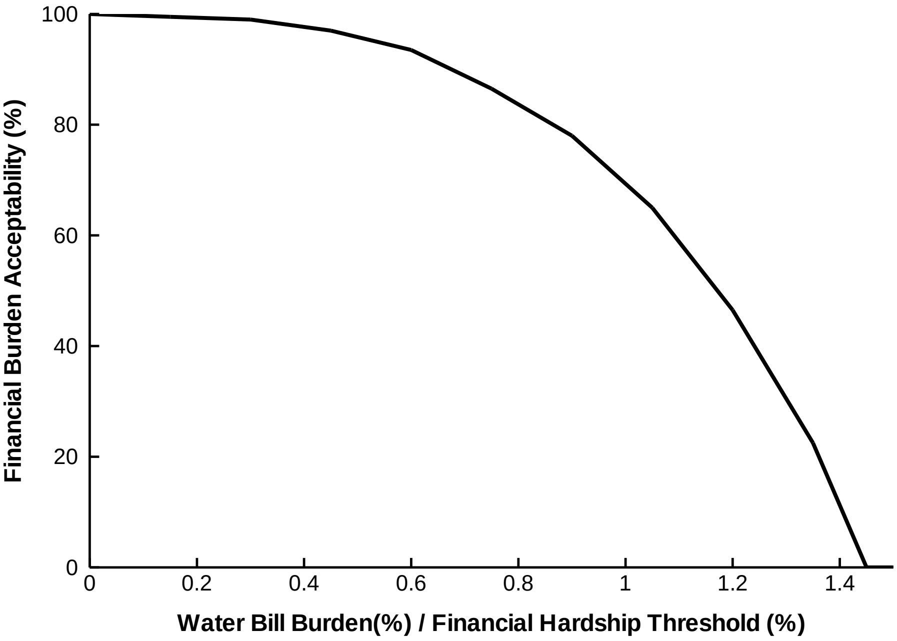


Figure 5.11: Assumed $Financial\ Burden\ Acceptability$ function

$Service\ Level\ Acceptability$ is assumed as a function of the highly deteriorated pipes fraction, PFN_{HD} (Section 5.5.1). It is postulated that the function can be of the form as shown in Figure 5.12. This figure shows implies that when the network is in relatively better condition (PFN_{HD} is low), the customers do not recognize the need for service improvements and hence see little justification for fee hikes. Stated another way, when the network's service performance is relatively good (indicated by a low PFN_{HD}), the customers' willingness to accept fee hikes is low. However, when the network is deteriorated (PFN_{HD} is high), customers become more willing to accept fee hikes with the expectation that the utility invests higher revenues in improving service performance. This assumption is depicted with the rising limb of the curve in Figure 5.12.

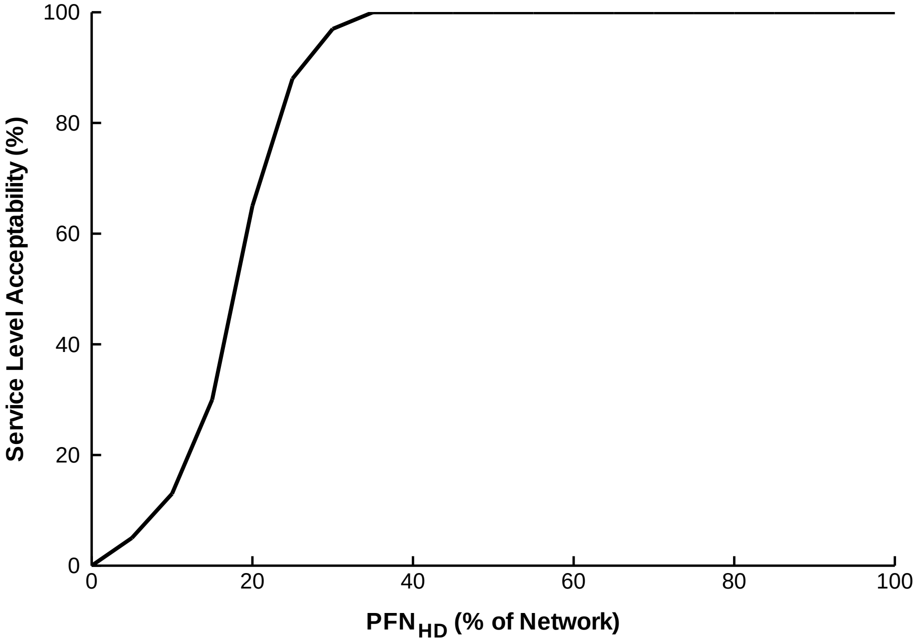


Figure 5.12: Assumed $Service\ Level\ Acceptability$ function

The functional forms of $Financial\ Burden\ Acceptability$ and $Service\ Level\ Acceptability$ (shown in Figures 5.11 and 5.12, respectively) are included as the defaults in the model. The user can override the defaults by using graphical input utility in the user interface of the model (Section 5.6.2). When a value of 100% is assigned to every ordinate in Figure 5.11, then the constraint imposed by $Financial\ Burden\ Acceptability$ is effectively removed. Similarly, $Service\ Level\ Acceptability$ can be switched off by assigning a value of zero to every ordinate in Figure 5.12.

Detailed equations governing this sector are presented in Appendix C.

5.5.4 Policy levers

The model includes the following policy levers for testing various network management strategies:

1. preferred network rehabilitation rate;
2. maximum tolerable number of watermain breaks;
3. pipe stocks that are rehabilitated;
4. maximum tolerable fraction of highly deteriorated pipes;
5. desired elimination period for highly deteriorated pipes fraction;
6. debt capacity;
7. desired reserve fraction; and
8. maximum allowable fee hike rate.

Preferred network rehabilitation rate is the percentage of total network length that a user specifies to be rehabilitated annually. The actual rehabilitation rate can be less than this preferred rate if sufficient cash is not available to carry out rehabilitation or there are simply not enough pipes in the pipe stocks slated for rehabilitation.

Maximum tolerable number of watermain breaks is used as the basis for assigning pipes to the highly deteriorated category. When the expected number of breaks for a pipe stock is greater than the tolerable limit, then the pipe stock is considered as a highly deteriorated pipes stock.

Pipes are rehabilitated that belong to stocks selected by the user for rehabilitation. It is logical to assume that all stocks for which the expected number of breaks exceeds the tolerable limit need to be rehabilitated. Flexibility is provided, in the model, such that the user has to explicitly choose pipe stocks for rehabilitation.

As long as the highly deteriorated pipes constitute a fraction of the total network that is less than the maximum tolerable fraction, then the rehabilitation proceeds at a rate not greater than the user specified preferred rehabilitation rate. But when the fraction of highly deteriorated pipes exceeds the tolerance limit, the model calculates a new rehabilitation rate such that all highly deteriorated pipes are rehabilitated over a desired elimination period (next policy lever). The financing constraints still remain in effect. This policy lever is used to simulate a crisis driven management approach where the network is allowed to deteriorate until a point that it can no longer be ignored. Maximum tolerable fraction of worse pipes can be set to any value from 0 to 100 percent of the network. The desired elimination period for worse condition pipes is effective only in conjunction with the previous policy lever (maximum tolerable fraction of highly deteriorated pipes) and can be assigned a value of 1 or more years.

Debt capacity is the percentage of total annual revenue up to which debt service charges are allowed to increase. Setting it to zero implies a ‘pay as you go’ financing strategy where all expenditures are paid for through current revenues and no debt is issued. In the Province of Ontario, municipalities are restricted from borrowing that results in debt service charges exceeding 25% of the revenues (Ontario, 2003).

Utilities do not necessarily lower their fees even when revenues exceed current expenditures. Instead the resulting surplus can be set aside to build cash reserves that are drawn upon in future. Such reserves act us buffers against the need to abruptly increase fees when large capital expenditures are incurred. In the model, the targeted reserve level is specified as the replacement value of a fraction of the whole network. For example, specifying a desired reserve level of 1% means that the reserve should contain enough cash to finance rehabilitation of 1% of the network.

Maximum allowable fee hike rate can be assigned any non-negative percentage value. Assigning an arbitrary high value to the maximum allowable fee hike rate implies that water fee can increase without any constraint. This means that the user is making an assumption that feedback loop $\mathbf{B_2}$ (Figure 5.4) does not exist.

Finally, it should be noted that in addition to the model objects described in this section, the complete model contains several auxiliary objects to perform all the needed calculations. All the model objects and equations are provided in Appendix C.

5.6 System Dynamics Model Application

Data requirements and uses of the presented system dynamics model are discussed in the following sections.

5.6.1 Data requirements

The following discussion describes data required in each sector of the model.

5.6.1.1 Watermain distribution network

Watermain pipes in the current model are classified into stocks on the basis of pipe material and age. Thus, these two attributes are required for every pipe in the network. Information about additional attributes is needed when pipe stocks are disaggregated further according to those attributes.

To estimate the volume of leaked water from the network, the model needs to be provided with leakage fraction (percentage of total consumption) values for each pipe stock. In the absence of any detailed water audits, such fractions can be estimated using information about the total volume of leaked water for the whole network and attributes of pipe stocks. Such a procedure essentially follows Walski (1987) and is based on the assumption that leakage from pipes increases at the same rate (percent per year) as the watermain breaks.

The lengths of new pipes added to the network for growing population can be estimated using typical ratios such as those provided in Burnside (2005).

5.6.1.2 Finance sector

The unit cost of rehabilitating a pipe (dollars per metre) is required to calculate capital expenditures incurred during a given year and project cash requirements for maintaining the desired rehabilitation rate of the network. Unit cost for a representative pipe size and material can be estimated from available utility data for past projects following the procedure in Unger et al. (2011). Selvakumar et al. (2002) and RS Means (www.rsmeans.com) are other published sources for this information.

Unit costs of maintenance (dollars per metre per year) for each category of pipe stocks in the watermain distribution sector are required. Ideally these should be estimated from a utility’s own historic maintenance costs. But in many cases, the historic costs may be aggregated and not linked to pipes of specific attributes. In such cases, one could rely on approximate values reported in published literature such as Burnside (2005).

Future values for unit cost of treated water (dollars per cubic metre) can be obtained from the operator of water treatment plant while taking into account its future operational and capital expenditure requirements for various levels of treatment plant capacities.

Savings rate depends upon the utility's preference for the specific kinds of financial instruments in which it invests its cash reserves. It is likely that a utility invests in risk free instruments such as the Bank of Canada treasury bills. The expected rate of return on such instruments can be estimated from historic data and used as the savings rate in the model.

Borrowing rate depends upon the market in which the utility seeks to borrow, as well as, its own credit rating (Moody's, 1999). In the Province of Ontario, public water utilities have access to loans through a provincial crown corporation which publishes its lending rates (Infrastructure Ontario, 2011).

The model has the capability to inflate the various unit prices using the respective inflation rates. Cost inflation indices for specific purposes are generally available such as the consumer price index (for inflating administrative costs), the water main and sewer pipe construction inflation rates developed by Unger et al. (2011) (for inflating unit cost of rehabilitation and maintenance).

5.6.1.3 Consumer sector

This sector requires information such as current water demand, price elasticity of water demand, minimum water demand, demand adjustment period, current population and population growth rate.

Information about current water demand, current population, and projected population growth rate is generally available. The remaining three parameters need to be estimated through consumer and market surveys. Estimation of price elasticity of demand has been the subject of many studies (for a survey see Agthe and Billings, 2003). Its reported values vary considerably in range and selecting a value needs careful evaluation of factors such as climate and socio-economic conditions to check their applicability to a particular case. Choosing a value for demand adjustment period involves consideration of whether the price elasticity of demand captures short-run or long-run effects. Minimum demand of water can be selected based on expert judgement while taking into account water demand values in other cities of comparable characteristics.

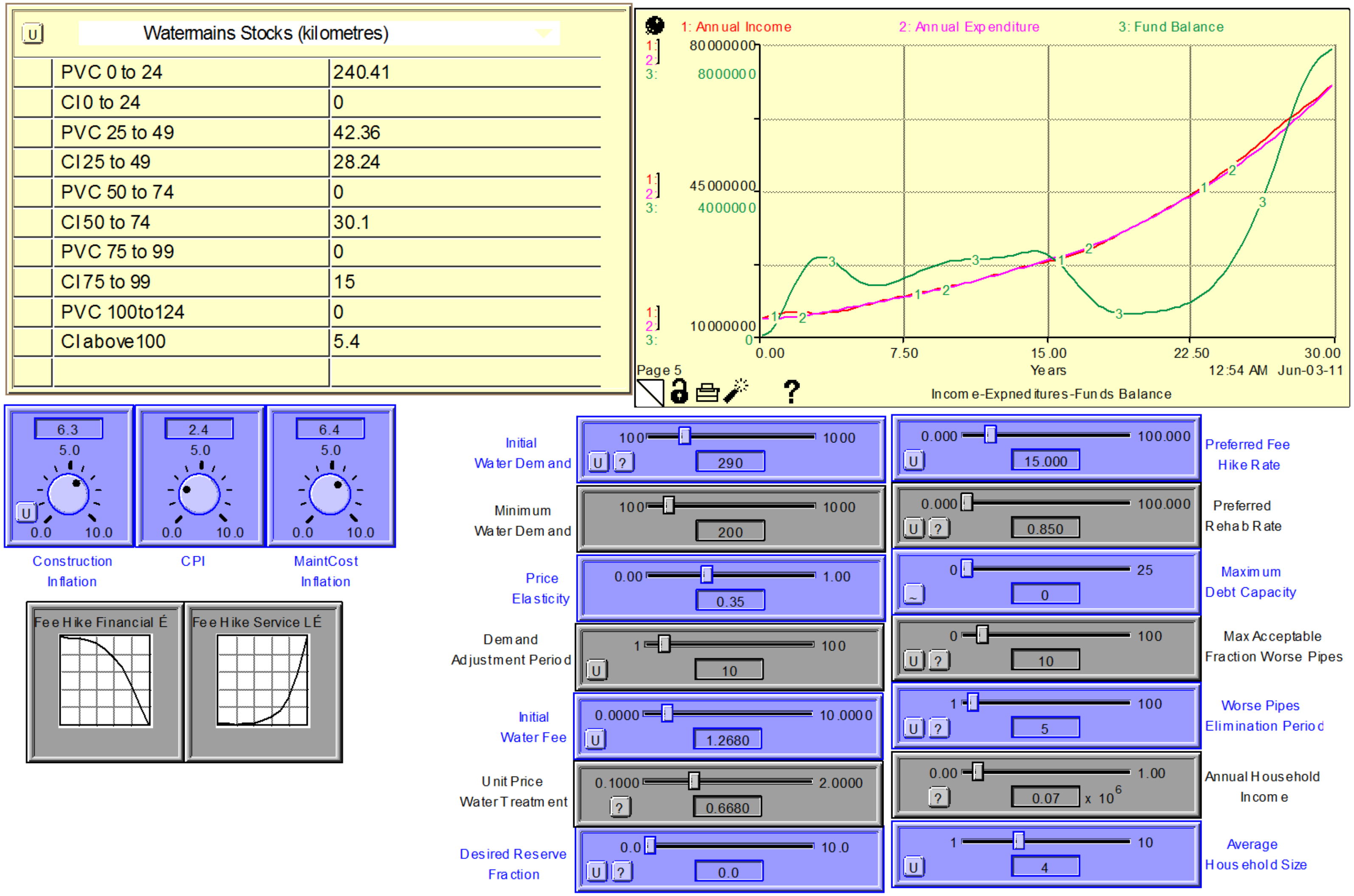
5.6.2 Model uses

Figures 5.7, 5.8 and 5.10 present snapshots of the structural level of the model. At this level, model objects are connected to each other and equations (Appendix C) are written. For policy testing and formulation, a user friendly interface is provided (Figure 5.13). At this level, the user can input required data using tables, knob, and slider input devices. Results are displayed graphically, as well as, stored in tabular format for detailed inspection. These functionalities allow the user to quickly alter values of various parameters to conduct ‘what if’ analysis without the need to make changes at the structural level of the model.

The model can be used to develop short- and long-term management plans for water distribution networks. Different financial and rehabilitation strategies can be devised using the policy levers discussed in Section 5.5.4. The impact of these strategies on system performance can be simulated using the model.

Alternative strategies can be compared in terms of performance indicators such as:

- Annual fund balance over the simulation period;
- Total life cycle costs over the simulation period;
- Annual capital and operational expenditures;
- Annual and total life-cycle interest payments on debt (if any);
- Water fee and average water bill for a typical household;
- Annual number of watermain breaks;
- Fraction of the network comprised of highly deteriorated pipes;
- Annual water consumption;
- Annual volume of leaked water;



Watermains Stocks (kilometres)	
PVC 0 to 24	240.41
CI 0 to 24	0
PVC 25 to 49	42.36
CI 25 to 49	28.24
PVC 50 to 74	0
CI 50 to 74	30.1
PVC 75 to 99	0
CI 75 to 99	15
PVC 100to124	0
CI above100	5.4

Construction Inflation 6.3 (0.0 – 10.0)
CPI 2.4 (0.0 – 10.0)
MaintCost Inflation 6.4 (0.0 – 10.0)

Initial Water Demand 100 – 1000: 290
Minimum Water Demand 100 – 1000: 200
Price Elasticity 0.00 – 1.00: 0.35
Demand Adjustment Period 1 – 100: 10
Initial Water Fee 0.0000 – 10.0000: 1.2680
Unit Price Water Treatment 0.1000 – 2.0000: 0.6680
Desired Reserve Fraction 0.0 – 10.0: 0.0
Preferred Fee Hike Rate 0.000 – 100.000: 15.000
Preferred Rehab Rate 0.000 – 100.000: 0.850
Maximum Debt Capacity 0 – 25: 0
Max Acceptable Fraction Worse Pipes 0 – 100: 10
Worse Pipes Elimination Period 1 – 100: 5
Annual Household Income 0.00 – 1.00: 0.07 x 10^6
Average Household Size 1 – 10: 4

Figure 5.13: User interface level of the model in Stella®.

The impact of various financing strategies can be evaluated in terms of financial sustainability. Affordability of a public good, such as potable water, should be a major concern of many stakeholders. It is interesting to note that consumers prefer that increases in water fee, if warranted, be implemented steadily without abrupt fluctuations (Falp and Le Masurier 2009). The model allows examination of the impacts of different management strategies on the water fee in terms of consistency and stability over time. The maximum allowable fee hike rate is a policy lever that can be used to specifically test management strategies in this respect.

Because of long service life, watermain networks typically serve several generations. An important consideration in developing strategic plans is to check how the costs (fees) and benefits (service performance levels) are shared between different generations. This can be accomplished by running the model for various scenarios and simulation periods (20, 50, 100 years).

Govindarajan et al. (2010) report that consumers in Oslo, Norway were willing to pay additional water bills provided they were convinced, in a transparent manner, about the need and justification for expenditures. Several studies have shown the effectiveness of system dynamics models in this respect (Stave, 2003; Cockerill et al., 2004; Cockerill, 2010). Stakeholders with no prior experience of modelling have been found to quickly grasp concepts conveyed using system dynamics models and to develop a better understanding of the policy issue. Thus, the presented model can be utilized by utility managers in building support for their network rehabilitation and financing strategies among various stakeholders such as political decision makers, consumer, and environmental groups.

5.7 Conclusions

This study makes two unique contributions to the body of knowledge. First, a detailed causal loop diagram for the management of a water distribution network is developed. Second, the qualitative causal loop diagram is operationalized as a decision support tool using the system dynamics methodology.

The presented causal loop diagram is the first known attempt to lay out the interrelationships among system components, for a financially self-sustaining water utility, using a formal technique. These interrelationships are based on an understanding of the system developed through literature review, extensive interactions with local utility operators and research collaboration with industry professionals. The presented causal loop diagram can be critiqued and improved upon, thus advancing the state of knowledge.

The causal loop diagram can be used to easily follow how perturbation of one system component reverberates throughout the system. This can especially be useful to mitigate the effects of silo-based organizational culture prevalent in water utilities.

An important contribution of the causal loop diagram is that it establishes the existence of several interacting feedback loops. These feedback loops demonstrate that the management of water distribution networks constitutes a complex dynamic system for which traditional management tools used in the area are deemed inadequate.

The presented system dynamics model is the first known decision support tool to quantitatively simulate the impact of interrelationships and feedback loops in financially sustainable management of a water distribution network. The model can be used to develop management policies that meet the requirements of regulatory mandates.

The presented model can be calibrated and tested using a municipal water utility as case study.

Chapter 6

Conclusions, Contributions and Future Recommendations

6.1 General Conclusions

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

It is shown that management of municipal water distribution and wastewater collection networks constitutes a complex dynamic system. The system is characterized by interconnections and feedback loops. Existing asset management tools do not capture this dynamic complexity and hence are found unsuitable to help Canadian municipalities meet the regulatory requirements of financial self-sustainability.

A causal loop diagram is a useful formal tool to qualitatively identify interacting feedback loops involved in the management of water distribution and wastewater collection networks. Furthermore, a causal loop diagram can be employed as the basis for developing a mathematical simulation model, easily communicating the scope and limitations of the later.

System dynamics is an acceptable methodology to model interconnections within and across physical, financial, and consumer sectors of watermain distribution and wastewater collection network models.

Simulation results (Chapters 2 and 4) show that feedback loops have significant influence on system behaviour. Moreover, different financing and rehabilitation strategies can achieve similar total life-cycle costs of operating the networks but with significantly different financial and service performance implications for the consumers.

Available utility data is found incomplete to allow a robust analysis of current management strategies.

6.2 Contributions

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

1. Management of municipal watermain distribution and wastewater collection networks is framed as a complex dynamic problem.

2. Causal loop diagrams are developed for financially sustainable management of watermain distribution and wastewater collection networks.
3. The novel approach of system dynamics modelling is used to integrate physical, financial, and consumer sectors of watermain distribution and wastewater collection networks management.
4. System dynamics based models are developed for management of watermain distribution network and wastewater collection network management. Both models include a variety of policy levers allowing formulation of different financing and rehabilitation strategies. Alternative strategies can be compared in terms of financial and service performance levels.
5. A methodology is presented to parameterize system dynamics model for management of municipal wastewater collection networks, using existing data sources.
6. Critical data elements are identified which need to be collected and recorded by water and wastewater utilities.

It is hoped that the models developed in this research will help Canadian water and wastewater utilities develop short- and long-term management plans that conform to regulatory requirements in terms of financial sustainability while meeting customer expectations of service performance and justifiable user fees.

6.3 Directions for Future Research

The most important contribution of this research is that it presents an innovative framework for integrating physical infrastructure, financial, and social elements of water and wastewater infrastructure management. Furthermore, using the underlying conceptual ideas of this framework, it is possible to further refine and expand the scope of the presented watermain and wastewater infrastructure models. Specific recommendations for future research work are listed as follows:

- In the presented model for wastewater collection network, unit price of sewage treatment is included as an exogenous variable. It can be transformed into an endogenous variable by introducing physical infrastructure and financial sectors for wastewater treatment plant. The treatment plant physical sector should model the planning, construction, operation and decommissioning phases. Treatment plant physical sector would receive information inputs from the wastewater pipes infrastructure and consumer sectors regarding extraneous flows and domestic sewage flows, respectively. The treatment plant financial sector can be similar to the wastewater pipes financial sector. The major difference being that unlike the user fee for wastewater service, determination of unit price of sewage treatment does not have to be constrained. Cash reserves and debt capacity can be modelled independently for the wastewater treatment plant and collection network or shared between the two depending upon the governance structure of the utility.

- Following the same concepts as described for wastewater treatment, it is recommended that the unit price of water treatment is modelled as an endogenous variable by including physical infrastructure and financial sectors for water treatment plant.
- The watermains distribution network and wastewater collection network models presented in this research should be integrated within one model. The two models can be connected in their current forms as well as after including the models for water and wastewater treatment plants.
- Price elasticity of water demand is also modelled as a constant in both the watermains distribution and wastewater collection network models. As an improvement, it can be transformed into an exogenous variable whose value varies with the prevailing user fee value. For even further realistic representation, a sub-model for determining water demand can be developed that in addition to price signals accounts for the effects of water conservation campaigns and diffusion/adoption of water conserving technologies.
- Research is needed to better understand consumer preferences for service performance levels and their willingness to accept corresponding user fees. Results of such surveys can be incorporated to improve the consumer sectors of the presented models.
- Implement network and program level repairs, rehabilitation, and replacement optimization strategies.

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Appendix A

Demonstration system dynamics model for management of water and wastewater pipe networks

A1 Physical Infrastructure Sector

A1.1 $Condition\_Group\_20$

Type	Stock
Units	Kilometres
Equation	$Condition\_Group\_20(t) = Condition\_Group\_20(t - dt) + (Renewal - Deterioration\_20\_to\_40) * dt$
Description	Lengths of pipes in the condition state 20.
Initial Value	140
Reference for definition of independent variables	
$Renewal$	Object A1.2
$Deterioration\_20\_to\_40$	Object A1.3

A1.2 $Renewal$

Type	Flow
Units	Kilometres per year
Equation	$Renewal = Rehab\_Length$
Description	Represents the annual rehabilitation of pipes. Moves pipe lengths from stock $Condition\_Group\_100$ to stock $Condition\_Group\_20$
Initial Value	Not applicable
Reference for definition of independent variables	
$Rehab\_Length$	Object A1.13

A1.3 $Deterioration\_20\_to\_40$

Type	Flow
Units	Kilometres per year
Equation	$Deterioration\_20\_to\_40 = Condition\_Group\_20/20$
Description	Represents the ageing process of the pipes. Moves pipe lengths from stock $Condition\_Group\_20$ to stock $Condition\_Group\_40$.
Initial Value	Not applicable
Reference for definition of independent variables	
$Condition\_Group\_20$	Object A1.1

A1.4 $Condition\_Group\_40$

Type	Stock
Units	Kilometres
Equation	$Condition\_Group\_40(t) = Condition\_Group\_40(t - dt) + (Deterioration\_20\_to\_40 - Deterioration\_40\_to\_60) * dt$
Description	Lengths of pipes in the condition state 40.
Initial Value	280
Reference for definition of independent variables	
$Deterioration\_20\_to\_40$	Object A1.3
$Deterioration\_40\_to\_60$	Object A1.5

A1.5 $\boldsymbol{Deterioration\_40\_to\_60}$

Type	Flow
Units	Kilometres per year
Equation	$Deterioration\_40\_to\_60 = Condition\_Group\_40/20$
Description	Represents the ageing process of the pipes. Moves pipe lengths from stock $Condition\_Group\_40$ to stock $Condition\_Group\_60$.
Initial Value	Not applicable
Reference for definition of independent variables	
$Condition\_Group\_40$	Object A1.4

A1.6 $\boldsymbol{Condition\_Group\_60}$

Type	Stock
Units	Kilometres
Equation	$Condition\_Group\_60(t) = Condition\_Group\_60(t - dt) + (Deterioration\_40\_to\_60 - Deterioration\_60\_to\_80) * dt$
Description	Lengths of pipes in the condition state 60.
Initial Value	140
Reference for definition of independent variables	
$Deterioration\_40\_to\_60$	Object A1.5
$Deterioration\_60\_to\_80$	Object A1.7

A1.7 $\boldsymbol{Deterioration\_60\_to\_80}$

Type	Flow
Units	Kilometres per year
Equation	$Deterioration\_60\_to\_80 = Condition\_Group\_60/20$
Description	Represents the ageing process of the pipes. Moves pipe lengths from stock $Condition\_Group\_60$ to stock $Condition\_Group\_80$.
Initial Value	Not applicable
Reference for definition of independent variables	
$Condition\_Group\_60$	Object A1.6

A1.8 $\boldsymbol{Condition\_Group\_80}$

Type	Stock
Units	Kilometres
Equation	$Condition\_Group\_80(t) = Condition\_Group\_80(t - dt) + (Deterioration\_60\_to\_80 - Deterioration\_80\_to\_100) * dt$
Description	Lengths of pipes in the condition state 80.
Initial Value	105
Reference for definition of independent variables	
$Deterioration\_60\_to\_80$	Object A1.7
$Deterioration\_80\_to\_100$	Object A1.9

A1.9 $\boldsymbol{Deterioration\_80\_to\_100}$

Type	Flow
Units	Kilometres per year
Equation	$Deterioration\_80\_to\_100 = Condition\_Group\_80/20$
Description	Represents the ageing process of the pipes. Moves pipe lengths from stock $Condition\_Group\_80$ to stock $Condition\_Group\_100$.
Initial Value	Not applicable
Reference for definition of independent variables	
$Condition\_Group\_80$	Object A1.8

A1.10 $\boldsymbol{Condition\_Group\_100}$

Type	Stock
Units	Kilometres
Equation	$Condition\_Group\_100(t) = Condition\_Group\_100(t - dt) + (Deterioration\_80\_to\_100 - Renewal) * dt$
Description	Lengths of pipes in the condition state 100.
Initial Value	35
Reference for definition of independent variables	
$Deterioration\_80\_to\_100$	Object A1.9
$Renewal$	Object A1.2

A1.11 $Total\_Length\_Pipes$

Type	Converter
Units	Kilometres
Equation	$Total\_Length\_Pipes = Condition\_Group\_20 + Condition\_Group\_40 + Condition\_Group\_60 + Condition\_Group\_80 + Condition\_Group\_100$
Description	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	
$Condition\_Group\_20$	Object A1.1
$Condition\_Group\_40$	Object A1.4
$Condition\_Group\_60$	Object A1.6
$Condition\_Group\_80$	Object A1.8
$Condition\_Group\_100$	Object A1.10

A1.12 $Average\_Condition$

Type	Converter
Units	Dimensionless
Equation	$Average\_Condition = (Condition\_Group\_20 \times 20 + Condition\_Group\_40 \times 40 + Condition\_Group\_60 \times 60 + Condition\_Group\_80 \times 80 + Condition\_Group\_100 \times 100)/Total\_Length\_Pipes$
Description	This is the average condition of all pipes in the network.
Initial Value	49
Reference for definition of independent variables	
$Condition\_Group\_20$	Object A1.1
$Condition\_Group\_40$	Object A1.4
$Condition\_Group\_60$	Object A1.6
$Condition\_Group\_80$	Object A1.8
$Condition\_Group\_100$	Object A1.10
$Total\_Length\_Pipes$	Object A1.11

A1.13 $Rehab\_Length$

Type	Converter
Units	Kilometres per year
Equation	$Rehab\_Length = Total\_Length\_Pipes * Rehab\_Fraction/100$
Description	Represents the length of pipes rehabilitated every year. The number 100 appearing in the above equation converts the $Rehab\_Fraction$ from percent into fraction.
Initial Value	Not applicable
Reference for definition of independent variables	
$Total\_Length\_Pipes$	Object A1.11
$Rehab\_Fraction$	Object A1.14

A1.14 $Rehab\_Fraction$

Type	Converter (Constant)
Units	Percent per year
Equation	Not applicable because it is a constant
Description	It is the fraction of total length of the network that is to be rehabilitated 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 100.

A2 Consumer Sector

A2.1 $Water\_Demand$

Type	Stock
Units	Litres per capita per day
Equation	$Water\_Demand(t) =$ $Water\_Demand(t - dt) - (Demand\_Change) * dt$
Description	It is the average water consumed by a person in a day.
Initial Value	300
Reference for definition of independent variables	
$Demand\_Change$	Object A2.2

A2.2 $Demand\_Change$

Type	Flow
Units	Litres per capita per day per year
Equation	$Demand\_Change = MIN((User\_Fees - DELAY(User\_Fees, 1))/DELAY(User\_Fees, 1)) * Elasticity\_of\_Demand * Water\_Demand, (Water\_Demand - Minimum\_Demand))$
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 $User\_Fees$ 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 $Minimum\_Demand$. 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 i.e., $Water\_Demand$ can decrease as a result of an increase in $User\_Fees$ but if there is a decrease in $User\_Fees$ then the stock $Water\_Demand$ remains unchanged.
Initial Value	Not applicable
Reference for definition of independent variables	
$User\_Fees$	Object A3.9
$Elasticity\_of\_Demand$	Object A2.3
$Water\_Demand$	Object A2.1
$Minimum\_Demand$	Object A2.4

A2.3 $Elasticity\_of\_Demand$

Type	Converter (Constant)
Units	Percent/Percent (dimensionless)
Equation	Not applicable because it is a constant
Description	It is equal to the percentage change in $Water\_Demand$ divided by the percentage change in $User\_Fees$. 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 $Elasticity\_of\_Demand$ 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.

A2.4 $Minimum\_Demand$

Type	Converter (Constant)
Units	Litres per capita per day
Equation	Not applicable because it is a constant.
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 $User\_Fees$. Its value is specified by the user for any simulation scenario and it then remains constant throughout the simulation.
Initial Value	200

A2.5 $Total\_Water\_Consumption$

Type	Converter
Units	Cubic metres per year
Equation	$Total\_Water\_Consumption =$ $SMTH3\ (Water\_Demand, Demand\_Adjustment\_Period) *$ $Population * 365/1000$
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 $Water\_Demand$ (Object A2.1), $SMTH3(\ )$ function implements the new value over the $Demand\_Adjustment\_Period$. For further discussion please refer to Section 4.2 and Figure 4. The number 365 in the equation converts the daily water demand o yearly water consumption. The number 1000 in the denominator converts litres to cubic metres.
Initial Value	Not applicable

Reference for definition of independent variables	
$Water\_Demand$	Object A2.1
$Demand\_AdjustmentPeriod$	Object A2.6
$Population$	Object A2.7

A2.6 $Demand\_Adjustment\_Period$

Type	Converter (Constant)
Units	Years
Equation	Not applicable since it is a constant
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.

A2.7 $Population$

Type	Converter (Constant)
Units	Persons
Equation	Not applicable because it is a constant
Description	It is the total number of people served by the water utility.
Initial Value	A value of 100,000 is used in this study and is assumed constant over the simulation period.

A3 Finance Sector

A3.1 $Funds\_Balance$

Type	Stock
Units	Dollars
Equation	$Funds\_Balance(t) =$ $Funds\_Balance(t - dt) + (Revenue - OpEx - CapEx) * dt$
Description	Represents the utility’s funds balance.
Initial Value	0
Reference for definition of independent variables	
$Revenue$	Object A3.2
$OpEx$	Object A3.3
$CapEx$	Object A3.4

A3.2 $Revenue$

Type	Flow
Units	Dollars per year
Equation	$Revenue = User\_Fees * Total\_Water\_Consumption$
Description	Represents the utility’s income.
Initial Value	Not applicable
Reference for definition of independent variables	
$User\_Fees$	Object A3.9
$Total\_Water\_Consumption$	Object A2.5

A3.3 $OpEx$

Type	Flow
Units	Dollars per year
Equation	$OpEx = Unit\_Price\_OpEx * Total\_Length\_Pipes * 1000 * (1 + Condition\_Multiplier\_OpEx/100)$
Description	$OpEx$ or operational expenditures are the annual costs associated with purchase of treated drinking water, treatment and disposal of wastewater, pumping of water and wastewater in their respective pipe networks, maintenance activities (flushing and minor repairs) and emergency expenditures (watermain breaks, sewer backups, etc). $OpEx$ has two components – a fixed component which does not change for a given length of pipe network, and a variable component which is dependent upon the average age of pipes in the network. $OpEx$ is inflated by the factor $AgeMultiplier\_OpEx$. The constant 1000 is used to convert $Total\_Length\_Pipes$ from kilometres to metres. The constant 100 is used to convert $AgeMultiplier\_OpEx$ from percentage to fraction.
Initial Value	Not applicable
Reference for definition of independent variables	
$Unit\_Price\_OpEx$	Object A3.6
$Total\_Length\_Pipes$	Object A1.11
$Condition\_Multiplier\_OpEx$	Object A3.7

A3.4 $CapEx$

Type	Flow
Units	Dollars per year
Equation	$CapEx = Renewal * 1000 * Unit\_Price\_CapEx$
Description	$CapEx$ or capital expenditures represent annual pipe rehabilitation costs. The constant 1000 is used to convert $Renewal$ from kilometres per year to metres per year.
Initial Value	Not applicable
Reference for definition of independent variables	
$Renewal$	Object A1.2
$Unit\_Price\_CapEx$	Object A3.5

A3.5 $Unit\_Price\_CapEx$

Type	Converter (Constant)
Units	Dollars per metre
Equation	Not applicable because it is a constant
Description	It is the cost of rehabilitation of one metre of an old (above 80 years) pipe.
Initial Value	1,000

A3.6 $Unit\_Price\_OpEx$

Type	Converter (Constant)
Units	Dollars per metre per year
Equation	Not applicable because it is a constant
Description	Unit cost (per metre) of operating and maintaining the network.
Initial Value	50

A3.7 $Condition\_Multiplier\_OpEx$

Type	Converter
Units	Dimensionless
Equation	$Condition\_Multiplier\_OpEx = GRAPH(Average\_Condition)$ $(0.00,0.00), (10.0,1.50), (20.0,3.50), (30.0,6.50), (40.0,11.0), (50.0,18.0), (60.0,26.0), (70.0,38.5), (80.0,55.0), (90.0,75.0), (100,100)$
Description	$Condition\_Multiplier\_OpEx$ is used in this model to inflate the $Unit\_Price\_OpEx$, depending upon the average condition of pipes in the network. It is formulated as a graphic function of the variable $Average\_Condition$. Each set of points in the parentheses above represent a point on the graph plotted between $Average\_Condition$ (the independent variable or absicca) and $Condition\_Multiplier\_OpEx$ (the dependent variable or ordinate). Please also refer to Section 4.3 and Figure 5.
Initial Value	As given in the above graph relationship.
Reference for definition of independent variables	
$Average\_Condition$	Object A1.12

A3.8 $TotalEx\_ToDate$

Type	Stock
Units	Dollars
Equation	$TotalEx\_ToDate(t) = TotalEx\_ToDate(t - dt) + (OpEx + CapEx) * dt$
Description	This stock represents the total accumulated expenditures incurred by the utility up to time t of the simulation.
Initial Value	0
Reference for definition of independent variables	
$OpEx$	Object A3.3
$CapEx$	Object A3.4

A3.9 $User\_Fees$

Type	Stock
Units	Dollars per cubic metre
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 metre of water consumed. In this study a constant volumetric $User\_Fees$ is assumed. This means that customers pay the same price for one cubic metre of water regardless of their consumption levels. In this study, $User\_Fees$ is assumed to cover the charges for both drinking water and wastewater services.
Initial Value	3.75
Reference for definition of independent variables	
$User\_Fee\_Hike$	Object A3.10
$User\_Fee\_Decline$	Object A3.11

A3.10 $User\_Fee\_Hike$

Type	Flow
Units	Dollars per cubic metre per year
Equation	$User\_Fee\_Hike = IF\ (Funds\_Balance > Maximum\_Funds\_Balance)\ THEN\ 0\ ELSE\ (Required\_Revenue * Zero\_Fund\_Balance/Total\_Water\_Consumption - User\_Fees)/1$
Description	This flow represents the annual rate of increase of $User\_Fees$. The conditional statement employed in the above equation first checks whether $Funds\_Balance$ is greater than its specified upper limit ($Maximum\_Funds\_Balance$), if true there is no increase in $User\_Fees$ i.e. $User\_Fee\_Hike = 0$ during the time interval. If $Funds\_Balance$ is not greater than $Maximum\_Funds\_Balance$ the increase in $User\_Fees$ is the difference between the required level of $User\_Fees$($Required\_Revenue/Total\_Water\_Consumption$) and its current value. It should be noted that even in such a case $User\_Fee\_Hike$ can still be equal to zero if $Zero\_Fund\_Balance$ has been set equal to zero. The number 1 in the equation represents the $User\_Fee\_Hike$ implementation period and has units of years.
Initial Value	Not applicable
Reference for definition of independent variables	
$Funds\_Balance$	Object A3.1
$Maximum\_Funds\_Balance$	Object A3.14
$Required\_Revenue$	Object A3.13
$Zero\_Fund\_Balance$	Object A3.16
$Total\_Water\_Consumption$	Object A2.5
$User\_Fees$	Object A3.9

A3.11 $User\_Fee\_Decline$

Type	Flow
Units	Dollars per cubic metre per year
Equation	$User\_Fee\_Decline = IF\ (Funds\_Balance > Maximum\_Funds\_Balance)\ THEN\ ((User\_Fees - (Expenditures * 1 - Funds\_Balance)/Total\_Water\_Consumption)/1)\ ELSE\ 0$
Description	The above equation first checks whether $Funds\_Balance$ is greater than $Maximum\_Funds\_Balance$. If true, the $User\_Fees$ is decreased to a level to eliminate the surplus. If $Funds\_Balance$ does not exceed its specified upper limit ($Maximum\_Funds\_Balance$) then $User\_Fee\_Decline = 0$. The number 1 in the equation represents a period of 1 year.
Initial Value	Not applicable
Reference for definition of independent variables	
$Funds\_Balance$	Object A3.1
$Maximum\_Funds\_Balance$	Object A3.14
$User\_Fees$	Object A3.9
$Expenditures$	Object A3.12
$Total\_Water\_Consumption$	Object A2.5

A3.12 $Expenditures$

Type	Flow
Units	Dollars per year
Equation	$Expenditures = OpEx + CapEx$
Description	Represents the total annual expenditures incurred by the water utility.
Initial Value	Not applicable
Reference for definition of independent variables	
$OpEx$	Object A3.3
$CapEx$	Object A3.4

A3.13 $Required\_Revenue$

Type	Converter
Units	Dollars per year
Equation	$Required\_Revenue = IF\ (Funds\_Balance < Minimum\_Funds\_Balance)\ THEN\ (Expenditures - Funds\_Balance/1)\ ELSE\ Expenditures$
Description	It is the revenue required for next year if $Funds\_Balance$ is to be maintained at its desired level. The number 1 in the equation represents a period of 1 year.
Initial Value	Not applicable
Reference for definition of independent variables	
$Funds\_Balance$	Object A3.1
$Minimum\_Funds\_Balance$	Object A3.15
$Expenditures$	Object A3.12

A3.14 $Maximum\_Funds\_Balance$

Type	Converter
Units	Dollars
Equation	$Maximum\_Funds\_Balance = 1e308 * (1 - Zero\_Fund\_Balance)$
Description	It is the upper limit that is allowed to be reached by stock $Funds\_Balance$. 1e308 or 1×10^{308} is the largest number that can be used in the program. Hence, when $Zero\_Fund\_Balance = 0$, it means that stock $Funds\_Balance$ is allowed to grow unconstrained. When $Zero\_Fund\_Balance = 1 \Rightarrow Maximum\_Funds\_Balance = 0$ and $Funds\_Balance$ is constrained not to rise above 0.
Initial Value	0 or 1×10^{308} depending upon the user's selected value for $Zero\_Fund\_Balance$.
Reference for definition of independent variables	
$Zero\_Fund\_Balance$	Object A3.16

A3.15 $Minimum\_Funds\_Balance$

Type	Converter
Units	Dollars
Equation	$Minimum\_Funds\_Balance = -1e308 * (1 - Zero\_Fund\_Balance)$
Description	It is the lower limit that is allowed to be reached by stock $Funds\_Balance$. $-1e308$ or -1×10^{308} is the smallest number that can be used in the program. Hence, when $Zero\_Fund\_Balance = 0$, then it means that stock $Funds\_Balance$ is allowed to decline unconstrained. When $Zero\_Fund\_Balance = 1 \Rightarrow Minimum\_Funds\_Balance = 0$ and $Funds\_Balance$ is constrained not to fall below 0.
Initial Value	0 or -1×10^{308} depending upon the user's selected value for $Zero\_Fund\_Balance$.
Reference for definition of independent variables	
$Zero\_Fund\_Balance$	Object A3.16

A3.16 $Zero\_Fund\_Balance$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	Is a switch that allows the user to simulate a scenario with or without financial self-sustainability. It has a value of either 0 or 1. When $Zero\_Fund\_Balance$ is set equal to 0 the simulation does not have to maintain $Fund\_Balance$ at zero. Assigning a value of 1 to $Zero\_Fund\_Balance$ enforces financial self-sustainability where $Fund\_Balance$ is maintained at zero.
Initial Value	0 or 1.

Appendix B

System dynamics model for management of wastewater collection networks

B1 Wastewater Collection Sector

B1.1 $\boldsymbol{SwPipes\ Grade\ 1[M]}$

Type	Stock.
Units	Kilometres
Equation	$SwPipes\ Grade\ 1[\boldsymbol{M}](t) = SwPipes\ Grade\ 1[\boldsymbol{M}](t - dt) - SwPipes\ Deterioration\ 1{,}2[\boldsymbol{M}] \times dt$ for $\boldsymbol{M} = 1, \ldots, n-1$ where n is the number of different pipe materials in the network; and $SwPipes\ Grade\ 1[\boldsymbol{M}](t) = SwPipes\ Grade\ 1[\boldsymbol{M}](t - dt) + \left(\sum_{\boldsymbol{G}=4}^{5} \sum_{\boldsymbol{K}=1}^{n} SwPipes\boldsymbol{G}\ Rehab[\boldsymbol{K}] + New\ Pipes\ Installation - SwPipes\ Deterioration\ 1{,}2[\boldsymbol{M}]\right) \times dt$ for $\boldsymbol{M} = n$ and where $\boldsymbol{G}$ is the internal condition grade of pipes.
Description	ICG 1 pipes of $\boldsymbol{M}^{\text{th}}$ material in the network having n different pipe materials. It is assumed that pipes which are newly installed are all made of one (n^{th}) material. Similarly, when pipes in ICG 4 and ICG 5 are rehabilitated, these are assumed to be replaced with pipes of same (n^{th}) material. Thus stocks for ICG 1 pipes of all other ($n-1$) materials have only one (out)flow that is pipes move out of these stocks but do not enter them (through new installation or rehabilitation). While the stock of ICG 1 pipes of n^{th} material has additional flows as well. These inflows represent rehabilitation of pipes from ICG 4 and 5 to ICG 1 and installation of new ICG 1 pipes.

Reference for definition of independent variables	
$SwPipes\ Deterioration\ 1{,}2[\boldsymbol{M}]$	Object B1.2

B1.2 $SwPipes\ Deterioration\ \boldsymbol{G},\boldsymbol{G}+\mathbf{1}[\boldsymbol{M}]$

Type	Flow
Units	Kilometres per year
Equation	$SwPipes\ Deterioration\ \boldsymbol{G},\boldsymbol{G}+1[\boldsymbol{M}]=\frac{SwPipes\ Grade\ \boldsymbol{G}[\boldsymbol{M}]}{Average\ Duration\ in\ Grade[\boldsymbol{M},\boldsymbol{G}]}$ where $\boldsymbol{G}=1,2,3$ and 4 is the internal condition grade of pipes and $\boldsymbol{M}=1,\dots,n$ is the pipe material for a network having n different pipe materials.
Description	It represents deterioration of pipes from internal condition grade $\boldsymbol{G}$ to internal condition grade $\boldsymbol{G}+\mathbf{1}$. Thus this flow moves pipes of different materials from their respective stocks of lower ICG to the higher ICG stocks. Note that this outflow exists only for stocks of pipes up to ICG 4 because ICG 5 is the final deteriorated condition grade and there is no further deterioration from stocks of ICG 5 pipes.
Reference for definition of independent variables	
$SwPipes\ Grade\ \boldsymbol{G}[\boldsymbol{M}]$	Object B1.1 for $\boldsymbol{G}=1$ Object B1.8 for $\boldsymbol{G}=2$ and 3 Object B1.9 for $\boldsymbol{G}=4$ Object B1.10 for $\boldsymbol{G}=5$
$Avg\ Duration\ in\ Grade[\boldsymbol{M},\boldsymbol{G}]$	Object B1.11

B1.3 $New\ Pipes\ Installation$

Type	Flow
Units	Kilometres per year
Equation	$New\ Pipes\ Installation=Population\ Growth\times Pipes\ to\ Populaion\ Ratio$
Description	This flow represents annual expansion of the network to service growing population.
Reference for definition of independent variables	
$Population\ Growth$	Object B2.13
$Pipes\ to\ Population\ Ratio$	Object B1.4

B1.4 $\boldsymbol{Pipes\ to\ Population\ Ratio}$

Type	Converter
Units	Kilometres per person
Equation	Not applicable as it is assumed constant.
Description	It is the length of pipes to service an additional consumer.

B1.5 $\boldsymbol{Rehab\ Grade\ 4}$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	It is a switch that allows the user to specify whether or not ICG 4 pipes are to be rehabilitated? It is assigned a value of either 0 or 1 at the beginning of simulation, which then remains constant throughout the simulation. When $Rehab\ Grade\ 4$ is set equal to 0 ⇒ $SwPipes4\ Rehab[\boldsymbol{M}] = 0$ that is ICG 4 pipes are not rehabilitated. Conversely, when assigned a value of 1, ICG 4 can be rehabilitated provided that pipes are available in ICG 4 stocks to be rehabilitated and also funds are available to carry out such rehabilitation.

B1.6 $\boldsymbol{SwPipes4\ Rehab}[\boldsymbol{M}]$

Type	Flow
Units	Kilometres per year
Equation	$SwPipes4\ Rehab[\boldsymbol{M}] = Achievable\ Rehab\ Length\ 4 \times Rehab\ Grade\ 4$ for $\boldsymbol{M} = 1$ is a pipe material among a total of n different pipe materials comprising the whole network. $SwPipes4\ Rehab[\boldsymbol{M}] = \left(Achievable\ Rehab\ Length\ 4 - \sum_{\boldsymbol{K}=1}^{\boldsymbol{M}-1} SwPipes4\ Rehab[\boldsymbol{K}]\right) \times Rehab\ Grade\ 4$ for $\boldsymbol{M} = 2, \ldots .\, n$ where n is the total number of different pipe materials that constitute the network.
Description	This flow represents annual rehabilitation of ICG 4 pipes made of $\boldsymbol{M}^{\text{th}}$ pipe material among the n different pipe materials comprising the whole network. The total length of ICG 4 pipes that can be rehabilitated in a given year is determined as $Achievable\ Rehab\ Length\ 4$, as explained later. Hence the annual rehabilitation of ICG 4 pipes for all n pipe materials together cannot exceed $Achievable\ Rehab\ Length\ 4$. It should also be noted that $SwPipes4\ Rehab[\boldsymbol{M}]$ cannot be numerically greater than the prevailing value of stock $SwPipes\ Grade\ 4[\boldsymbol{M}]$ at any time during the simulation regardless of the value determined through the above equation. In other words, $SwPipes4\ Rehab[\boldsymbol{M}]$ can at most move to ICG 1 stock (rehabilitate) the length of pipes available in the source ICG 4 stock $SwPipes\ Grade\ 4[\boldsymbol{M}]$.

Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ 4$	Object B4.15
$Rehab\ Grade\ 4$	Object B1.5

B1.7 $\boldsymbol{SwPipes5\ Rehab[M]}$

Type	Flow
Units	Kilometres per year
Equation	$SwPipes5\ Rehab[\boldsymbol{M}] = Achievable\ Rehab\ Length\ 5$ for $\boldsymbol{M} = 1$ is a pipe material among a total of n different pipe materials comprising the whole network. $SwPipes5\ Rehab[\boldsymbol{M}] = Achievable\ Rehab\ Length\ 5 - \sum_{\boldsymbol{K}=1}^{\boldsymbol{M}-1} SwPipes5\ Rehab[\boldsymbol{K}]$ for $\boldsymbol{M} = 2, \ldots. n$ where n is the total number of different pipe materials that constitute the network.
Description	This flow represents annual rehabilitation of ICG 5 pipes made of $\boldsymbol{M}^{\text{th}}$ pipe material among the n different pipe materials comprising the whole network. The total length of ICG 5 pipes that can be rehabilitated in a given year is determined as $Achievable\ Rehab\ Length\ 5$, as explained later. Hence the annual rehabilitation of ICG 5 pipes for all n pipe materials together cannot exceed $Achievable\ Rehab\ Length\ 5$. It should also be noted that $SwPipes5\ Rehab[\boldsymbol{M}]$ cannot be numerically greater than the prevailing value of stock $SwPipes\ Grade\ 5[\boldsymbol{M}]$ at any time during the simulation regardless of the value determined through the above equation. In other words, $SwPipes5\ Rehab[\boldsymbol{M}]$ can at most move to ICG 1 stock (rehabilitate) the length of pipes available in the source ICG 5 stock $SwPipes\ Grade\ 5[\boldsymbol{M}]$.
Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ 5$	Object B4.14

B1.8 $\boldsymbol{SwPipes\ Grade\ G}[\boldsymbol{M}]$

Type	Stock.
Units	Kilometres
Equation	$SwPipes\ Grade\ \boldsymbol{G}[\boldsymbol{M}](t) = SwPipes\ Grade\ \boldsymbol{G}[\boldsymbol{M}](t - dt) + (SwPipes\ Deterioration\ \boldsymbol{G} - 1, \boldsymbol{G}[\boldsymbol{M}] - SwPipes\ Deterioration\ \boldsymbol{G}, \boldsymbol{G} + 1[\boldsymbol{M}]) \times dt$ for internal condition grades $\boldsymbol{G} = 2,3$ and pipe materials $\boldsymbol{M} = 1, \ldots, n$ where n is the number of different pipe materials in the network.
Description	This stock represents pipes in each of internal condition grades 2 and 3 for each of pipe materials $\boldsymbol{M} = 1, \ldots, n$. Thus, this model objects represents 2 ($\boldsymbol{G}$) x n ($\boldsymbol{M}$) stocks. Each of these stocks has an inflow and outflow associated with it. Inflow $SwPipes\ Deterioration\ \boldsymbol{G} - 1, \boldsymbol{G}[\boldsymbol{M}]$ represents lengths of pipes arriving from the previous ICG stock for the respective pipe material. While, outflow $SwPipes\ Deterioration\ \boldsymbol{G}, \boldsymbol{G} + 1[\boldsymbol{M}]$ represents departures of pipe lengths to the next higher ICG stock for the respective pipe material.
Reference for definition of independent variables	
$SwPipes\ Deterioration\ \boldsymbol{G} - 1, \boldsymbol{G}[\boldsymbol{M}]$	Object B1.2
$SwPipes\ Deterioration\ \boldsymbol{G}, \boldsymbol{G} + 1[\boldsymbol{M}]$	Object B1.2

B1.9 $\boldsymbol{SwPipes\ Grade\ 4[M]}$

Type	Stock.
Units	Kilometres
Equation	$SwPipes\ Grade\ 4[\boldsymbol{M}](t) = SwPipes\ Grade\ 4[\boldsymbol{M}](t - dt) + (SwPipes\ Deterioration\ 3{,}4[\boldsymbol{M}] - SwPipes\ Deterioration\ 4{,}5[\boldsymbol{M}] - SwPipes4\ Rehab[\boldsymbol{M}]) \times dt$ for $\boldsymbol{M} = 1, \dots, n$ where n is the total number of different pipe materials in the network.
Description	This stock represents ICG 4 pipes for the $\boldsymbol{M}^{\text{th}}$ pipe material. Pipe lengths in this stock arrive due to deterioration of ICG 3 pipes through flow $SwPipes\ Deterioration\ 3{,}4[\boldsymbol{M}]$ while pipe lengths leave from this stock either by deteriorating to ICG 5 ($SwPipes\ Deterioration\ 4{,}5[\boldsymbol{M}]$) or being rehabilitated to ICG 1 through flow $SwPipes4\ Rehab[\boldsymbol{M}]$.

Reference for definition of independent variables	
$SwPipes\ Deterioration\ 3{,}4[\boldsymbol{M}]$	Object B1.2
$SwPipes\ Deterioration\ 4{,}5[\boldsymbol{M}]$	Object B1.2
$SwPipes4\ Rehab[\boldsymbol{M}]$	Objects B1.6

B1.10 $\boldsymbol{SwPipes\ Grade}\ \mathbf{5}[\boldsymbol{M}]$

Type	Stock.
Units	Kilometres
Equation	$SwPipes\ Grade\ 5[\boldsymbol{M}](t) = SwPipes\ Grade\ 5[\boldsymbol{M}](t - dt) + (SwPipes\ Deterioration\ 4{,}5[\boldsymbol{M}] - SwPipes5\ Rehab[\boldsymbol{M}]) \times dt$ for $\boldsymbol{M} = 1, \dots, n$ where n is the total number of different pipe materials in the network.
Description	This stock represents ICG 5 pipes for the $\boldsymbol{M}^{\text{th}}$ pipe material. Pipe lengths in this stock arrive due to deterioration of ICG 4 pipes through flow $SwPipes\ Deterioration\ 4{,}5[\boldsymbol{M}]$ while pipe lengths can leave from this stock by being rehabilitated to ICG 1 through flow $SwPipes5\ Rehab[\boldsymbol{M}]$.

Reference for definition of independent variables	
$SwPipes\ Deterioration\ 4{,}5[\boldsymbol{M}]$	Object B1.2
$SwPipes5\ Rehab[\boldsymbol{M}]$	Objects B1.7

B1.11 $\boldsymbol{Average\ Duration\ in\ Grade}[\boldsymbol{M}, \boldsymbol{G}]$

where $\boldsymbol{M} = 1, \dots, n$ for network comprising of n different pipe materials, and $\boldsymbol{G} = 1, 2,\ 3,\ and\ 4$ is the internal condition grade of a pipe.

Type	Converter.
Units	Years
Equation	Not applicable, it is a constant
Description	It represents the average length of time for which a pipe of material $\boldsymbol{M}$ remains in internal condition grade $\boldsymbol{G}$ before deteriorating to the next $(\boldsymbol{G} + \mathbf{1})$ internal condition grade.

B1.12 $\boldsymbol{Cumulative\ I\&I\ Volume}$

Type	Stock.
Units	Cubic metres
Equation	$Cumulative\ I\&I\ Volume(t) = Cumulative\ I\&I\ Volume(t-dt) + (Annual\ I\&I\ Flow) \times dt$
Description	Cumulative volume of extraneous sewage flows due to infiltration.
Reference for definition of independent variables	
$Annual\ I\&I\ Flow$	Object B1.13

B1.13 $\boldsymbol{Annual\ I\&I\ Flow}$

Type	Flow
Units	Cubic metres per year
Equation	$Annual\ I\&I\ Flow = Avg\ Daily\ I\&I\ Flow \times Days\ Per\ Year$
Description	Represents the annual extraneous sewage flows due to infiltration.
Reference for definition of independent variables	
$Avg\ Daily\ I\&I\ Flow$	Object B1.14
$Days\ Per\ Year$	Object B1.18

B1.14 $\boldsymbol{Avg\ Daily\ I\&I\ Flow}$

Type	Converter
Units	Cubic metres per day
Equation	$Avg\ Daily\ I\&I\ Flow = \sum_{\boldsymbol{G}=1}^{5} Daily\ I\&I\ by\ Grade[\boldsymbol{G}]$ where $\boldsymbol{G}$ is the internal condition grade of pipes.
Description	Represents the total daily volume of extraneous sewage flows for pipes in all $\boldsymbol{G}$ (1 to 5) internal condition grades.
Reference for definition of independent variables	
$Daily\ I\&I\ by\ Grade[\boldsymbol{G}]$	Object B1.15

B1.15 $\boldsymbol{Daily\ I\&I\ by\ Grade}[\boldsymbol{G}]$

Type	Converter
Units	Cubic metres per day
Equation	$Daily\ I\&I\ by\ Grade[\boldsymbol{G}] = I\&I\ Rate\ by\ Grade[\boldsymbol{G}] \times \sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{G}]$ for $\boldsymbol{M} = 1, \dots, n$ where n is the number of different pipe materials in the network; and $\boldsymbol{G} = 1, \dots, 5$ is the internal condition grade of pipes.
Description	Represents the daily volume of extraneous sewage flows for pipes in each internal condition grade.
Reference for definition of independent variables	
$I\&I\ Rate\ by\ Grade[\boldsymbol{G}]$	Object B1.16
$SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{G}]$	Object B4.2

B1.16 $\boldsymbol{I\&I\ Rate\ by\ Grade}[\boldsymbol{G}]$

Type	Converter
Units	Cubic metres per day per kilometre
Equation	Not applicable (constant)
Description	Represents the daily volume of extraneous sewage flows per unit length of pipes in each internal condition grade $\boldsymbol{G} = 1, \dots, 5$.
Reference for definition of independent variables	

B1.17 $Annual\ Total\ Flows$

Type	Converter
Units	Cubic metres per year
Equation	$Annual\ Total\ Flows = Annual\ I\&I\ Flow + Sanitary\ Sewage\ Flow$
Description	It is the total annual volume of sewage collected by the network and represents the volume that is treated at the wastewater treatment plant. The utility has to pay for the treatment of this total volume instead of only that generated by the consumers ($Sanitary\ Sewage\ Flow$).

Reference for definition of independent variables	
$Annual\ I\&I\ Flow$	Object B1.13
$Sanitary\ Sewage\ Flow$	Object B2.7

B1.18 $Days\ Per\ Year$

Type	Converter
Units	Days per year
Equation	$Days\ Per\ Year = 365$
Description	It is used to convert days into year.

B2 Consumer Sector

B2.1 $Water\ Demand$

Type	Stock
Units	Litres per capita per day
Equation	$Water\ Demand(t) = Water\ Demand(t - dt) - (Price\ Induced\ Reduction) * dt$
Description	It is the average daily volume of water consumed by a person.

Reference for definition of independent variables	
$Price\ Induced\ Reduction$	Object B2.2

B2.2 $\boldsymbol{Price\ Induced\ Reduction}$

Type	Flow
Units	Litres per capita per day per year
Equation	$Price\ Induced\ Reduction = MIN((Water\ Demand - New\ Water\ Demand) / Demand\ Adjustment\ Period, (Water\ Demand - Minimum\ Demand))$
Description	It is the change in water demand caused by an increase in $Sewage\ Fee$. 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 $Price\ Induced\ Reduction$ does not cause value of $Water\ Demand$ to fall below its lower limit specified as $Minimum\ Demand$. It should also be noted that the flow $Price\ Induced\ Reduction$ is a unidirectional outflow for stock $Water\ Demand$. This means that $Price\ Induced\ Reduction$ can only assume non-negative values i.e., $Water\ Demand$ can decrease as a result of an increase in $Sewage\ Fee$ but if there is a decrease in $Sewage\ Fee$ then the stock $Water\ Demand$ remains unchanged.

Reference for definition of independent variables	
$Water\ Demand$	Object B2.1
$New\ Water\ Demand$	Object B2.3
$Demand\ Adjustment\ Period$	Object B2.11
$Minimum\ Water\ Demand$	Object B2.10

B2.3 *New Water Demand*

Type	Converter
Units	Litres per capita per day
Equation	$New\ Water\ Demand = Water\ Demand - Change\ in\ Water\ Demand$
Description	It is the new value that the stock $Water\ Demand$ is to attain as a result of price induced change in water demand. However, this new value is not attained instantaneously and instead is achieved over a $Demand\ Adjustment\ Period$ as shown in the formulation of $Price\ Induced\ Reduction$.
Reference for definition of independent variables	
$Water\ Demand$	Object B2.1
$Change\ in\ Water\ Demand$	Object B2.4

B2.4 *Change in Water Demand*

Type	Converter
Units	Litres per capita per day
Equation	$Change\ in\ Water\ Demand = MAX(Price\ Elasticity \times Change\ in\ Sewage\ Fee/100 \times Water\ Demand\ ,0)$
Description	It is the change in water demand caused by an increase in sewage fee. In this study it is assumed that $Water\_Demand$ can only decrease as a result of price increases but does not increase if sewage fee falls. Hence, the function $MAX(\ )$ is used so that the change in demand is calculated only as a result of increases in sewage fee and is considered zero otherwise.
Reference for definition of independent variables	
$Price\ Elasticity$	Object B2.8
$Change\ in\ Sewage\ Fee$	Object B2.5
$Water\ Demand$	Object B2.1

B2.5 $Change\ in\ Sewage\ Fee$

Type	Converter
Units	Dimensionless
Equation	$Change\ in\ Sewage\ Fee = (Sewage\ Fee - Recent\ Average\ Sewage\ Fee)/Recent\ Average\ Sewage\ Fee \times 100$
Description	It is the percentage change in sewage fee compared to the average sewage fee over the recent past. It should be noted that instead of comparing annual changes in sewage fee, the comparison is made between current sewage fee with the average sewage over recent past. The underlying assumption is that consumers perceive the price signal in the recent historical context and react to them accordingly.

Reference for definition of independent variables	
$Sewage\ Fee$	Object B3.1
$Recent\ Average\ Sewage\ Fee$	Object B5.5

B2.6 $Water\ Consumption$

Type	Converter
Units	Cubic metres per year
Equation	$Water\ Consumption = Water\ Demand \times Population \times Days\ Per\ Year/1000$
Description	Annual volume of water consumed by (billed to) the customers. Right hand side of the equation is divided by 1000 to convert litres to cubic metres.

Reference for definition of independent variables	
$Water\ Demand$	Object B2.1
$Population$	Object B2.12
$Days\ Per\ Year$	Object B1.18

B2.7 $\boldsymbol{Sanitary\ Sewage\ Flow}$

Type	Converter
Units	Cubic metres per year
Equation	$Sanitary\ Sewage\ Flow = Water\ Consumption \times (100 - Consumptive\ Use\ Fraction)/100$
Description	Annual volume of sewage generated by consumers.
Reference for definition of independent variables	
$Water\ Consumption$	Object B2.6
$Consumptive\ Use\ Fraction$	Object B2.9

B2.8 $\boldsymbol{Price\ Elasticity}$

Type	Converter (Constant)
Units	Percent/Percent (dimensionless)
Equation	$Price\ Elasticity = 0.35$
Description	It is equal to the percentage change in $Water\ Demand$ divided by the percentage change in $Sewage\ Fee$. 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 a user wishes to specify a -0.35 value for the $Price\ Elasticity$ then they simply need to input it as 0.35

B2.9 $\boldsymbol{Consumptive\ Use\ Fraction}$

Type	Converter (Constant)
Units	Percent
Equation	$Consumptive\ Use\ Fraction = 10$
Description	Fraction of water consumed that is not returned to sewers as sewage. For example, water consumed in food preparation, car washing (escapes into storm sewers instead of sanitary sewers), watering lawns, evaporation from swimming pools.

B2.10 $\boldsymbol{Minimum\ Water\ Demand}$

Type	Converter (Constant)
Units	Litres per capita per day
Equation	$Minimum\ Water\ Demand = 200$
Description	It is the lower limit imposed on $Water\ Demand$. Hence, the value of $Water\ Demand$ cannot decrease beyond $Minimum\ Water\ Demand$. Its value is specified by the user for any simulation scenario and it then remains constant throughout the simulation.

B2.11 $\boldsymbol{Demand\ Adjustment\ Period}$

Type	Converter (Constant)
Units	Years
Equation	$Demand\ Adjustment\ Period = 10$
Description	It is the time period over which a change in $Water\ Demand$ is implemented.

B2.12 $\boldsymbol{Population}$

Type	Stock
Units	Persons
Equation	$Population(t) = Population(t - dt) + (Population\ Growth) * dt$
Description	It is the total number of consumers served by the water utility.
Reference for definition of independent variables	
$Population\ Growth$	Object B2.13

B2.13 $\boldsymbol{Population\ Growth}$

Type	Flow
Units	Persons per year
Equation	$Population\ Growth = Population * Population\ Growth\ Rate/100$
Description	It represents the annual increase in the population served by the water utility. It should be noted that this flow is bi-directional that is it can add to as well as subtract from the stock $population$. The decline in population occurs when the $Population\ Growth\ Rate$ is set to a negative value and represents communities with shrinking population base (e.g. ‘rust belt’ cities).
Reference for definition of independent variables	
$Population$	Object B2.12
$Population\ Growth\ Rate$	Object B2.14

B2.14 $\boldsymbol{Population\ Growth\ Rate}$

Type	Converter
Units	Percent per year
Equation	Not applicable since it is a constant.
Description	The user specifies its value at the start of simulation which then remains constant throughout the simulation. As noted in the description of $Population\ Growth$, this parameter can be assigned both positive and negative values.

B3 Finance Sector

B3.1 $Sewage\ Fee$

Type	Stock
Units	Dollars per cubic metre
Equation	$Sewage\ Fee(t) = Sewage\_Fee(t - dt) + (Sewage\ Fee\ Hike - Sewage\ Fee\ Decline) * dt$
Description	It is the amount (dollars) that the utility charges its customers for every cubic metre of sewage generated. In this study a constant volumetric $Sewage\ Fee$ is assumed. This means that customers pay the same price for each cubic metre of sewage regardless of their total consumption levels.

Reference for definition of independent variables

$Sewage\ Fee\ Hike$	Object B3.2
$Sewage\ Fee\ Decline$	Object B3.3

B3.2 $Sewage\ Fee\ Hike$

Type	Flow
Units	Dollars per cubic metre per year
Equation	$Sewage\ Fee\ Hike = (MIN((Current\ Year\ Fee\ Ceiling - Sewage\ Fee), (Required\ Sewage\ Fee)))/DT$
Description	This flow represents the annual increase in $Sewage\_Fee$. Use of the function $MIN(\ )$ensures that even when $Required\ Sewage\ Fee$ is higher, $Sewage\ Fee$ does not increase beyond the $Current\ Year\ Fee\ Ceiling$. Furthermore, division of right hand side of the equation by DT implements $Sewage\ Fee\ Hike$ over a single time step instead of continuous implementation over time.

Reference for definition of independent variables

$Current\ Year\ Fee\ Ceiling$	Object B5.9
$Sewage\ Fee$	Object B3.1
$Required\ Sewage\ Fee$	Object B3.4

B3.3 $\boldsymbol{Sewage\ Fee\ Decline}$

Type	Flow
Units	Dollars per cubic metre per year
Equation	$Sewage\ Fee\ Decline = IF\ (Sewage\ Fee < Required\ Sewage\ Fee)\ THEN\ 0\ ELSE\ MIN((Sewage\ Fee - 0.01), (Sewage\ Fee - Required\ Sewage\ Fee))$
Description	This outflow is used to reduce the $Sewage\ Fee$ if it is more than the $Required\ Sewage\ Fee$. If $Sewage\ Fee$ is less than the $Required\ Sewage\ Fee$ then $Sewage\ Fee\ Decline$ is set equal to zero and $Sewage\ Fee$ is not reduced. When $Sewage\ Fee$ has to be reduced, the use of $MIN(\quad)$ function ensures that the $Sewage\ Fee$ can decrease upto $Required\ Sewage\ Fee$ but never below 1 cent (\$0.01) per cubic metre. It should be noted that when $Sewage\ Fee\ Decline \neq 0$, the above equation implicitly implements the reduction in $Sewage\ Fee$ over a period of 1 year. This can be compared to the formulation of $Sewage\ Fee\ Hike$ where the increase in $Sewage\ Fee$ is achieved over a single time step (DT).
Reference for definition of independent variables	
$Sewage\ Fee$	Object B3.1
$Required\ Sewage\ Fee$	Object B3.4

B3.4 $\boldsymbol{Required\ Sewage\ Fee}$

Type	Converter
Units	Dollars per cubic metrer
Equation	$Required\ Sewage\ Fee = Next\ Year's\ Cash\ Required/Water\ Consumption$
Description	It represents the target level of $Sewage\ Fee$ that is required to generate $Next\ Year's\ \ Cash\ Required.$
Reference for definition of independent variables	
$Next\ Year's\ Cash\ Required$	Object B5.22
$Water\ Consumption$	Object B2.6

B3.5 $Working\ Capital$

Type	Stock
Units	Dollars
Equation	$Working\ Capital(t) = Working\ Capital(t - dt) + (Cash\ Inflow + Reserve\ Withdrawl - Cash\ Outflow - Reserve\ Deposit) * DT$
Description	It is the cash at hand with the utility.
Reference for definition of independent variables	
$Cash\ Inflow$	Object B3.6
$Reserve\ Withdrawl$	Object 0
$Cash\ Outflow$	Object B3.7
$Reserve\ Deposit$	Object B3.9
$Revenue$	Object B3.20

B3.6 $Cash\ Inflow$

Type	Flow
Units	Dollars per year
Equation	$Cash\ Inflow = Annual\ Income + Debt\ Issue$
Description	Annual amount of cash received by the water utility.
Reference for definition of independent variables	
$Annual\ Income$	Object 0
$Debt\ Issue$	Object B3.14

B3.7 $Cash\ Outflow$

Type	Flow
Units	Dollars per year
Equation	$Cash\ Outflow = Annual\ Expenditure + \ Principal\ Payment$
Description	Annual amount of cash paid out by the water utility.
Reference for definition of independent variables	
$Annual\ Expenditure$	Object B3.12
$Principal\ Payment$	Object B3.15

B3.8 $Reserve\ Withdrawl$

Type	Flow
Units	Dollars per year
Equation	$Reserve\ Withdrawl = Cash\ Required - Working\ Capital/DT$
Description	If $Cash\ Required$ is more than the available $Working\ Capital$ for the current time step then cash is withdrawn from the $Cash\ Reserve$.
Reference for definition of independent variables	
$Cash\ Required$	Object B5.21
$Working\ Capital$	Object B3.5

B3.9 $Reserve\ Deposit$

Type	Flow
Units	Dollars per year
Equation	$Reserve\ Deposit = Cash\ Inflow - Cash\ Outflow$
Description	If the cash received is more than the cash spent then the excess amount is transferred to the stock $Cash\ Reserve$.
Reference for definition of independent variables	
$Cash\ Inflow$	Object B3.6
$Cash\ Outflow$	Object B3.7

B3.10 $\boldsymbol{Cash\ Reserve}$

Type	Stock
Units	Dollars
Equation	$Cash\ Reserve(t) = Cash\ Reserve(t - dt) + (Reserve\ Deposit - Reserve\ Withdrawl) * DT$
Description	This stock represents the cash maintained by the water utility in excess of its current cash liabilities. When needed this reserve is drawn upon to make up for cash shortfall.

Reference for definition of independent variables	
$Reserve\ Withdrawl$	Object 0
$Reserve\ Deposit$	Object B3.9

B3.11 $\boldsymbol{Annual\ Income}$

Type	Converter
Units	Dollars per yearr
Equation	$Annual\ Income = Revenue + Interest\ Earnings$
Description	Annual income for the utility through sewage fees (revenue) and interest accrued on savings.

Reference for definition of independent variables	
$Revenue$	Object B3.20
$Interest\ Earnings$	Object B3.21

B3.12 $\boldsymbol{Annual\ Expenditure}$

Type	Converter
Units	Dollars per yearr
Equation	$Annual\ Expenditure = OpEx + CapEx + InterestEx$
Description	It is the total annual expenditure incurred by the utility. It has three components: $OpEx$, $CapEx$ and $InterestEx$.
$OpEx$	Object B3.22
$CapEx$	Object B3.23
$InterestEx$	Object 0

B3.13 $\boldsymbol{Debt}$

Type	Stock
Units	Dollars
Equation	$Debt(t) = Debt(t - dt) + (Debt\_Issue - Principal\_Payment) * DT$
Description	It represents the total amount of debt carried by the utility at any time during the simulation.
Reference for definition of independent variables	
$Debt\ Issue$	Object B3.14
$Principal\ Payment$	Object B3.15

B3.14 $\boldsymbol{Debt\ Issue}$

Type	Flow
Units	Dollars per year
Equation	$Debt\ Issue = MIN((Cash\ Required - Working\ Capital/DT - Reserve\ Withdrawl), Debt\ Available\ For\ Issue)$
Description	It represents new debt issued by the utility which adds to the existing $Debt$ level.
Reference for definition of independent variables	
$Cash\ Required$	Object B5.21
$Working\ Capital$	Object B3.5
$Reserve\ Withdrawl$	Object B3.8
$Debt\ Available\ For\ Issue$	Object B3.26

B3.15 $\boldsymbol{Principal\ Payment}$

Type	Flow
Units	Dollars per year
Equation	$Principal\ Payment = Annual\ Serials$
Description	When $Debt > 0$, then each year a portion of the outstanding principal amount is paid off and hence reduces $Debt$ level.
Reference for definition of independent variables	
$Annual\ Serials$	Object B3.16

B3.16 $\boldsymbol{Annual\ Serials}$

Type	Stock
Units	Dollars per year
Equation	$Annual\ Serials(t) = Annual\ Serials(t - dt) + (Serial\ Launch - Serial\ Retirement) * DT$
Description	It is the sum of all serials for outstanding debts issued that is required to be repayed every year until the debt for which the respective serials were issued are fully paid off.
Reference for definition of independent variables	
$Serial\ Launch$	Object B3.17
$Serial\ Retirement$	Object B3.18

B3.17 $\boldsymbol{Serial\ Launch}$

Type	Flow
Units	(Dollars per year) per year
Equation	$Serial\ Launch = Debt\ Issue/Amortization\ Period$
Description	In this study it is assumed that any long term debt that the utility takes on is to be paid off over the $Amortization\ Period$ in such a manner that the principal amount is repaid in equal annual installments plus interest on the outstanding portion of the principal. $Serial\ Launch$ represents that equal annual installment of principal repayment. Whenever a new debt is issued, a corresponding $Serial\ Launch$ is calculated for that debt and is stored in the $Annual\ Serials$ stock for the duration of $Amortization\ Period$.
Reference for definition of independent variables	
$Debt\ Issue$	Object B3.14
$Amortization\ Period$	Object B3.25

B3.18 $\boldsymbol{Serial\ Retirement}$

Type	Flow
Units	(Dollars per year) per year
Equation	$Serial\ Retirement_t = Serial\ Launch_{(t-Amortization\_Period)}$ where t is the prevailing simulation time (years).
Description	As mentioned in description of $Serial\ Launch$, a serial for each new debt is calculated and stored in the stock $Annual\ Serials$. After remaining there for a duration of $Amortization\ Period$, the serial is then removed whence the corresponding debt assumed has been paid off. $Serial\ Retirement$ represents this removal of a serial corresponding to the paid off debt.
Reference for definition of independent variables	
$Serial\ Launch$	Object B3.17
$Amortization\ Period$	Object B3.25

B3.19 $\boldsymbol{Fund\ Balance}$

Type	Stock
Units	Dollars
Equation	$Fund\ Balance(t)$ $= \ Funds\ Balance(t\ -\ dt)\ +\ (Revenue$ $+ Interest\ Earnings -\ OpEx - CapEx - InterestEx)\ *\ DT$
Description	Represents the utility's funds balance.
Reference for definition of independent variables	
$Revenue$	Object B3.20
$Interest\ Earnings$	Object B3.21
$OpEx$	Object B3.22
$CapEx$	Object B3.23
$InterestEx$	Object 0

B3.20 $Revenue$

Type	Flow
Units	Dollars per year
Equation	$Revenue = Sewage\ Fee * \ Water\ Consumption$
Description	Represents the utility's income derived from charging sewage fee.

Reference for definition of independent variables	
$Sewage\ Fee$	Object B3.1
$Water\ Consumption$	Object B2.6

B3.21 $Interest\ Earnings$

Type	Flow
Units	Dollars per year
Equation	$Interest\ Earnings = Savings\ Rate/100 * \ MAX(0, Fund\ Balance)$
Description	Represents the utility's income derived from interest earned on positive fund balance.

Reference for definition of independent variables	
$Savings\ Rate$	Object B3.29
$Fund\ Balance$	Object B3.19

B3.22 $\boldsymbol{OpEx}$

Type	Flow
Units	Dollars per year
Equation	$OpEx = \sum_{\boldsymbol{G}=1}^{5} Maintenance\ Expenditure[\boldsymbol{G}] + WWT\ Expenditure$ where $\boldsymbol{G} = 1,2,..,5$ is the internal condition grade of pipes.
Description	$OpEx$ or operational expenditures are the annual costs associated with management of network (administrative and government overheads), maintenance activities (flushing and minor repairs) and emergency expenditures (sewer backups, etc), treatment and disposal of wastewater, pumping of sewage in the network.
Reference for definition of independent variables	
$Maintenance\ Expenditure[\boldsymbol{G}]$	Object B3.30
$WWT\ Expenditure$	Object B3.31

B3.23 $\boldsymbol{CapEx}$

Type	Flow
Units	Dollars per year
Equation	$CapEx = \sum_{\boldsymbol{G}=4}^{5} Capital\ Expenditures[\boldsymbol{G}]$ where $\boldsymbol{G} = 4,5$ is the internal condition grade of pipes being rehabilitated.
Description	$CapEx$ or capital expenditures represent annual rehabilitation cost of pipes. In this study two kinds of rehabilitation expenditures are included: those incurred on rehabilitating pipes in internal condition grade 4 and those incurred on rehabilitating pipes in internal condition grade 5.
Reference for definition of independent variables	
$Capital\ Expenditures[\boldsymbol{G}]$	Object B3.35

B3.24 $\boldsymbol{Total\ Expensditure}$

Type	Stock
Units	Dollars
Equation	$Total\ Expenditure(t) = Total\ Expenditure(t - dt) + (OpEx + CapEx + InterestEx) \times DT$
Description	It represents the cumulative total (operational and capital) expenditures upto any time t (years) from the start of simulation.
Reference for definition of independent variables	
$OpEx$	Object B3.22
$CapEx$	Object B3.23
$InterestEx$	Object B3.27

B3.25 $\boldsymbol{Amortization\ Period}$

Type	Converter (constant)
Units	Years
Equation	Not applicable because it is a constant.
Description	It is the time period over which the utility pays off a long term debt.

B3.26 $Debt\ Available\ For\ Issue$

Type	Converter
Units	Dollars
Equation	$Debt\ Available\ For\ Issue = MAX(Annual\ Unused\ Debt\ Capacity * Amortization\ Period$
Description	Municipal governments are limited in the amount of debt that they can assume e.g., by provincial regulations in the Province of Ontario. This converter calculates the additional amount that the utility can borrow after taking into account its existing debt.
Reference for definition of independent variables	
$Annual\ Unused\ Debt\ Capacity$	Object B5.7
$Amortization\ Period$	Object B3.25

B3.27 $InterestEx$

Type	Flow
Units	Dollars per year
Equation	$InterestEx = Borrowing\ Rate/100 * Debt$
Description	It is the annual interest paid by the utility on its outstanding debt during a given year.
Reference for definition of independent variables	
$Borrowing\ Rate$	Object B3.28
$Debt$	Object B3.13

B3.28 $Borrowing\ Rate$

Type	Converter (constant)
Units	Percent per year
Equation	Not applicable because it is a constant.
Description	It is the interest rate for the debt carried by the utility.

B3.29 $\boldsymbol{Savings\ Rate}$

Type	Converter (constant)
Units	Percent per year
Equation	Not applicable because it is a constant.
Description	It is the rate at which the utility earns interest on its savings.
Reference for definition of independent variables	

B3.30 $\boldsymbol{Maintenance\ Expenditure}[\boldsymbol{G}]$

Type	Converter
Units	Dollars per year
Equation	$Maintenance\ Expenditure[\boldsymbol{G}] = Unit\ Cost\ Maintenance[\boldsymbol{G}] * \sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M},\boldsymbol{G}]\ /metre\ to\ km$ where $\boldsymbol{M} = 1, \dots, n$ is the number of pipe materials in the network; and $\boldsymbol{G} = 1, 2,\ 3,4$ and 5 is the internal condition grade of pipes.
Description	$Maintenance\ Expenditure$ represents expenses incurred by the utility on management of network (salaries, administrative and government overheads), maintenance activities (flushing and minor repairs) and emergency expenditures (sewer backups) and pumping of sewage in the network
Reference for definition of independent variables	
$Unit\ Cost\ Maintenance[\boldsymbol{G}]$	Object B3.32
$SwPipes\ Lengths[\boldsymbol{M},\boldsymbol{G}]$	Object B4.2
$metre\ to\ km$	Object B3.34

B3.31 $\boldsymbol{WWT\ Expenditure}$

Type	Converter
Units	Dollars per year
Equation	$WWT\ Expenditure = Annual\ Total\ Flows * Unit\ Price\ WWT$
Description	It represents the annual cost of treating and disposing off sewage.
Reference for definition of independent variables	
$Annual\ Total\ Flows$	Object B1.17
$Unit\ Price\ WWT$	Object B3.33

B3.32 $\boldsymbol{Unit\ Cost\ Maintenance[G]}$

where $\boldsymbol{G} = 1, 2,\ 3,4$ and 5 is the internal condition grade of pipes.

Type	Converter
Units	Dollars per metre per year
Equation	Not applicable since it a constant.
Description	It represents the annual cost per metre of pipe incurred on maintaining the network (salaries, administrative and government overheads), maintenance activities (flushing and minor repairs) and emergency expenditures (sewer backups) and pumping of sewage in the network.

B3.33 $\boldsymbol{Unit\ Price\ WWT}$

Type	Converter (constant)
Units	Dollars per cubic metre
Equation	Not applicable since it a constant.
Description	It is the cost for treatment and disposal of one cubic metre of sewage.

B3.34 $\boldsymbol{metre\ to\ km}$

Type	Converter (constant)
Units	Metres per kilometer
Equation	$meter\ to\ km = 1/1000$
Description	It is the conversion factor for converting metres to kilometres.

B3.35 $\boldsymbol{Capital\ Expenditure[G]}$

Type	Converter
Units	Dollars per year
Equation	$Capital\ Expenditure[\boldsymbol{G}]$ $= Unit\ Cost\ Rehabilitation[\boldsymbol{G}] * Capital\ Works[\boldsymbol{G}]/metre\ to\ km$ where $\boldsymbol{G} = 4$ and 5
Description	It is the annual expenditure incurred by the utility on rehabilitating pipes from internal condition grades 4 or 5 to internal condition grade 1.

Reference for definition of independent variables	
$Unit\ Cost\ Rehabilitation[\boldsymbol{G}]$	Object B3.36
$Capital\ Works[\boldsymbol{G}]$	Object B4.1
$metre\ to\ km$	Object B3.34

B3.36 $\boldsymbol{Unit\ Cost\ Rehabilitation[G]}$

where $\boldsymbol{G} = 4$ and 5

Type	Converter (constant)
Units	Dollars per metre
Equation	Not applicable since it a constant.
Description	It represents the per metre cost of rehabilitating a pipe in internal condition grade 4 or 5 to internal condition grade 1.

B4 Wastewater Collection Auxiliary Sector

B4.1 $\boldsymbol{Capital\ Works}[\boldsymbol{G}]$

Type	Converter
Units	Metres per year
Equation	$Capital\ Works[\boldsymbol{G}] = \sum_{\boldsymbol{M}} SwPipes\boldsymbol{G}\ Rehab[\boldsymbol{M}]$ for $\boldsymbol{M} = 1, \dots, n$ where n is the number of pipe materials in the network; and and $\boldsymbol{G} = 4$ and 5 is the internal condition grade of pipes that are rehabilitated.
Description	These represent the annual length of pipes rehabilitated.
Reference for definition of independent variables	
$SwPipes\boldsymbol{G}\ Rehab[\boldsymbol{M}]$	Object B1.6 for $\boldsymbol{G} = 4$ Object B1.7 for $\boldsymbol{G} = 5$

B4.2 $\boldsymbol{SwPipes\ Lengths}[\boldsymbol{M}, \boldsymbol{G}]$

where $\boldsymbol{M} = VitrifiedClay, Concrete$ and PVC; and $\boldsymbol{G} = 1,2,3,4$ and 5

Type	Converter
Units	Kilometres
Equation	$SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{G}] = SwPipes\ Grade\ \boldsymbol{G}[\boldsymbol{M}]$ for $\boldsymbol{M} = n$ where n is the number of different pipe materials in the network and $\boldsymbol{G} = 1, .., 5$ is the internal condition grade of pipes.
Description	This object stores the values of pipes lengths for each material and internal condition grade. For a network having n different pipe materials, this object stores $(n \times 5)$ values.
Reference for definition of independent variables	
$SwPipes\ Grade\ \boldsymbol{G}[\boldsymbol{M}]$	Object B1.1 for $\boldsymbol{G} = 1$ Object B1.8 for $\boldsymbol{G} = 2,3$ Object B1.9 for $\boldsymbol{G} = 4$ Object B1.10 for $\boldsymbol{G} = 5$

B4.3 *Average Condition Grade*

Type	Converter
Units	Dimensionless
Equation	$Average\ Condition\ Grade = \sum_{\boldsymbol{G}} \left\{ \left(\sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{G}] \right) \times \boldsymbol{G} \right\} / \left(\sum_{\boldsymbol{G}} \sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{G}] \right)$ for $\boldsymbol{M} = 1, \dots, n$ for a network having n different pipe materials; and and $\boldsymbol{G} = 1$ to 5
Description	It is the weighted average of the internal condition grade of pipes in the whole network.
Reference for definition of independent variables	
$SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{G}]$	Object B4.2

B4.4 *SwPipes Grade Fraction*[$\boldsymbol{G}$]

Type	Converter
Units	Dimensionless (Percentage)
Equation	$SwPipes\ Grade\ Fraction[\boldsymbol{G}] = \left(\sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{G}] \right) / \left(\sum_{\boldsymbol{K}=1}^{5} \sum_{\boldsymbol{M}} SewerLengths[\boldsymbol{M}, \boldsymbol{K}] \right) \times 100$ for $\boldsymbol{G} = 1,2,3,4$ and 5 $\boldsymbol{M} = 1, \dots, n$ where n is the number of different pipes materials in the network and $\boldsymbol{K} = 1$ to 5
Description	It is the fraction of sewers in various condition grades as a percentage of the total network length.
Reference for definition of independent variables	
$SwPipes\ Lengths[\boldsymbol{M}, \boldsymbol{K}]$	Object B4.2

B4.5 $\boldsymbol{Target\ Rehab\ Length}$

Type	Converter
Units	Kilometres per year
Equation	$Target\ Rehab\ Length = \sum_{\boldsymbol{G}=1}^{5}\sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M},\boldsymbol{G}] \times Network\ Rehab\ Fraction/100$ where $\boldsymbol{M} = 1,\dots,n$ and n is the number of different pipe materials in the network; and $\boldsymbol{G} = 1$ to 5
Description	It is the length of pipes that is slated for rehabilitation every year. It should be noted that the length that is actually rehabilitated can be less than the targeted length depending upon the length of pipes in internal condition grade(s) 5 (and/or 4) which is available for rehabilitation. Moreover, the actual length rehabilitated is also constrained by the cash availability for capital works.

Reference for definition of independent variables	
$SwPipes\ Lengths[\boldsymbol{M},\boldsymbol{G}]$	Object B4.2
$Network\ Rehab\ Fraction$	Object B4.8

B4.6 $\boldsymbol{Target\ Rehab\ Length\ Grade\ 5}$

Type	Converter
Units	Kilometres per year
Equation	$Target\ Rehab\ Length\ Grade\ 5$ $= MIN\left(\sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M}, 5]\ , Target\ Rehab\ Length\right)$ for $\boldsymbol{M} = 1, \dots, n$ where n is the total number of different pipe materials in the network.
Description	It is the annual length of pipes in internal condition grade 5 that is targeted for rehabilitation. The function $MIN(\ )$ensures that $Target\ Rehab\ Length\ Grade\ 5$ is equal to the lesser of pipe lengths in ICG 5 and $Target\ Rehab\ Length$. Actual length of ICG 5 pipes that is rehabilitated can be less than $Target\ Rehab\ Length\ Grade\ 5$ because of limited cash availability for rehabilitation.

Reference for definition of independent variables	
$SwPipes\ Lengths[\boldsymbol{M}, 5]$	Object B4.2
$Target\ Rehab\ Length$	Object B4.5

B4.7 $Target\ Rehab\ Length\ Grade\ 4$

Type	Converter
Units	Kilometres per year
Equation	$Target\ Rehab\ Length\ Grade\ 4$ $= MIN\left(\sum_{\boldsymbol{M}} SwPipes\ Lengths[\boldsymbol{M}, 4], (Target\ Rehab\ Length - Target\ Rehab\ Length\ Grade\ 5)\right) \times Rehab\ Grade\ 4$ for $\boldsymbol{M} = 1, \dots n$
Description	It is the length of pipes in internal condition grade 4 that is targeted for rehabilitation every year. This length cannot be greater than the length of pipes in ICG 4. Moreover, since rehabilitation of ICG 5 pipes has a higher priority as compared to that of ICG 4 pipes, therefore, $Target\ Rehab\ Length\ Grade\ 4$ cannot be greater than $(Target\ Rehab\ Length - Target\ Rehab\ Length\ Grade\ 5)$.

Reference for definition of independent variables	
$SwPipes\ Lengths[\boldsymbol{M}, 4]$	Object B4.2
$Target\ Rehab\ Length$	Object B4.5
$Target\ Rehab\ Length\ Grade\ 5$	Object B4.6
$Rehab\ Grade\ 4$	Object B1.5

B4.8 $\boldsymbol{Network\ Rehab\ Fraction}$

Type	Converter
Units	Percent of Network per year.
Equation	$Network\ Rehab\ Fraction = MAX(Preferred\ Network\ Rehab, New\ Rehab\ Rate \times Grade5\ Exceedance\ Flag)$
Description	It is the fraction of total network that is targeted for rehabilitation every year. It assumes a value that is greater of the $Preferred\ Network\ Reha$) assigned by the model user at start of simulation and $Rehab\ Rate$ which is calculated endogenously in the model. It should be noted that the fraction of network that is actually rehabilitated can be lesser due to limited cash available for rehabilitation.

Reference for definition of independent variables	
$Preferred\ Network\ Rehab$	Object B4.9
$New\ Rehab\ Rate$	Object B4.13
$Grade5\ Exceedance\ Flag$	Object B4.12

B4.9 $\boldsymbol{Preferred\ Network\ Rehab}$

Type	Converter (constant)
Units	Percent of network per year.
Equation	Not applicable because it is a constant
Description	It is the value specified by the user at the start of simulation representing the percentage of network that is to be rehabilitated every year.

B4.10 $\boldsymbol{Maximum\ Acceptable\ Grade5\ Fraction}$

Type	Converter (constant)
Units	Percentage of network.
Equation	Not applicable because it is a constant
Description	It is the percentage of network that the user specifies at the start of simulation. If ICG 5 fraction exceeds this maximum allowable limit then $Network\ Rehab\ Fraction$ no longer remains equal to $Preferred\ Network\ Rehab$ and assumes a value equal to the $New\ Rehab\ Rate$. It can be assigned any value between 0 to 100% (both inclusive).

B4.11 $\boldsymbol{Excess\ Grade5\ Removal\ Period}$

Type	Converter (constant)
Units	Years
Equation	Not applicable because it is a constant
Description	When $Sewer\ Grade\ Fraction[5]$ exceeds $Maximum\ Acceptable\ Grade5\ Fraction$ then the model calculates a new value ($Rehab\ Rate$) for $Network\ Rehab\ Fraction$ which eliminates $Sewer\ Grade\ Fraction[5]$ over a period of $Excess\ Grade5\ Removal\ Period$ years. It can assume a value from 1 to 100 years (both inclusive).

B4.12 $\mathbf{Grade5\ Exceedance\ Flag}$

Type	In the model this variable is calculated using a combination of stocks-flows-converters objects which is not provided here but the essential idea is represented by the following equation.
Units	Dimensionless
Equation	$Grade5\ Exceedance\ Flag = IF\ (Sewer\ Grade\ Fraction[5] > Maximum\ Acceptable\ Grade5\ Fraction)\ THEN\ 1\ ELSE\ 0$
Description	This is a switch which is turned on (assumes a value of 1) as soon as $Sewer\ Grade\ Fraction[5]$ becomes greater than the $Maximum\ Acceptable\ Grade5\ Fraction$. It is important to note that $Grade5\ Exceedance\ Flag$ does not turn off (assumes value of 0) when $Sewer\ Grade\ Fraction[5]$ again falls below $Maximum\ Acceptable\ Grade5\ Fraction$. Rather once turned on it stays that way until $Sewer\ Grade\ Fraction[5]$ has become less than a tolerance limit, which in this study is assumed 1%. This formulation is achieved in the model with the help of a stock/flow/converter structure which is not completely represented by the above equation. The idea for such a formulation is that once there is a ‘wake-up’ call due to the $Sewer\ Grade\ Fraction[5]$ exceeding the maximum allowable limit, the utility embarks upon an aggressive rehabilitation program to fix the problem. This aggressive program is aimed toward eliminating the Grade 5 fraction and once started, it continues until the Grade 5 fraction has been reduced to a tolerable limit (1% of network in this study) and not simply to a value below the maximum acceptable grade 5 fraction.

Reference for definition of independent variables	
$Sewer\ Grade\ Fraction[5]$	Object B4.4
$Maximum\ Acceptable\ Grade5\ Fraction$	Object B4.10

B4.13 $New\ Rehab\ Rate$

Type	In the model this variable is calculated using a combination of stocks-flows-converters objects which is not provided here but the essential idea is represented by the following equation.
Units	Percentage of network per year
Equation	$New\ Rehab\ Rate = Sewer\ Grade\_Fraction[5]/Excess\ Grade5\ Removal\ Period$ subject to the condition: $New\ Rehab\ Rate_t = MAX(New\ Rehab\ Rate_{t-1} + New\ Rehab\ Rate_t)$ where t is the current simulation time.
Description	This rehabilitation rate is calculated with the goal of eliminating $Sewer\ Grade\ Fraction[5]$ within a time period equal to $Excess\ Grade5\ Removal\ Period$. The constraint shown above is employed so that $New\ Rehab\ Rate$ does not start decreasing with decreasing value of $Sewer\ Grade\ Fraction[5]$ and is instead maintained at its maximum value until $Sewer\ Grade\ Fraction[5]$ has been reduced below a tolerable limit (1% of the network in this study).
Reference for definition of independent variables	
$Sewer\ Grade\ Fraction[5]$	Object B4.4
$Excess\ Grade5\ Removal\ Period$	Object B4.11

B4.14 $\boldsymbol{Achievable\ Length\ Rehab\ 5}$

Type	Converter
Units	Kilometres per year
Equation	$Achievable\ Length\ Rehab\ 5$ $= MIN(Target\ Rehab\ Length\ Grade\ 5, Cash\ Available\ Cap\ Works$ $/Unit\ Cost\ Rehabilitation[5] \times metre\ to\ km)$
Description	This object calculates the actual length of ICG 5 pipes that can be rehabilitated given the funds available for capital expenditures. Hence, if sufficient funds ($Cash\ Available\ Cap\ Works$) are not available then $Achievable\ Length\ Rehab\ 5$ can be less than the $Target\ Rehab\ Length\ Grade\ 5$.

Reference for definition of independent variables	
$Target\ Rehab\ Length\ Grade\ 5$	Object B4.6
$Cash\ Available\ Cap\ Works$	Object B5.14
$Unit\ Cost\ Rehabilitation[5]$	Object B3.36
$metre\ to\ km$	Object B3.34

B4.15 $\boldsymbol{Achievable\ Length\ Rehab\ 4}$

Type	Converter
Units	Kilometres per year
Equation	$Achievable\ Length\ Rehab\ 4$ $= MIN\big((Target\ Rehab\ Length$ $- Achievable\ Length\ Rehab\ 5), (Cash\ Available\ Rehab\ 4$ $/Unit\ Cost\ Rehabilitation[4] \times metre\ to\ km)\big)$
Description	This object calculates the actual length of ICG 4 pipes that can be rehabilitated given the funds available for rehabilitation of ICG 4 pipes.

Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ 5$	Object B4.14
$Cash\ Available\ Rehab\ 4$	Object B5.13
$Unit\ Cost\ Rehabilitation[4]$	Object B3.36
$metre\ to\ km$	Object B3.34

B5 Finance Auxiliary Sector

B5.1 $Average\ Revenue$

Type	In the model this variable is calculated using a combination of stocks-flows-converters objects which is not provided here but the essential idea is represented by the following equation.
Units	Dollars per year
Equation	$Average\ Revenue_t = \left(\sum_{k=t-Averaging\ Period}^{t-1} Revenue_k \right) / Averaging\ Period$ where t is the current time of simulation.
Description	It is the average of revenues over the most recent $Averaging\ Period$.
Reference for definition of independent variables	
$Revenue$	Object B3.20
$Averaging\ Period$	Object B5.2

B5.2 $Averaging\ Period$

Type	Converter (constant)
Units	Years
Equation	Not applicable because it is a constant.
Description	It is the time period over which revenue is averaged.

B5.3 $Last\ Year\ Fee$

Type	Converter
Units	Dollars per cubic metre
Equation	$LastYear\ Fee_t = Sewage\ Fee_{t-1}$ where t is the current time of simulation.
Description	It is the value of $Sewage\ Fee$, one year before the current time t
Reference for definition of independent variables	
$Sewage\ Fee$	Object B3.1

B5.4 $Recent\ Maximum\ Sewage\ Fee$

Type	In the model this variable is calculated using a combination of stocks-flows-converters objects which is not provided here but the essential idea is represented by the following equation.
Units	Dollars per cubic metre
Equation	$Recent\ Maximum\ Sewage\ Fee_t = MAX(Sewage\ Fee_{t-Horizon}, Sewage\ Fee_{t-Horizon+1}, \ldots\ldots, Sewage\ Fee_{t-1})$ where t is the current time of simulation.
Description	It is the maximum value of $Sewage\ Fee$ that has existed over the most recent time $Horizon$.
Reference for definition of independent variables	
$Sewage\ Fee$	Object B3.1
$Horizon$	Object B5.6

B5.5 $Recent\ Average\ Sewage\ Fee$

Type	In the model this variable is calculated using a combination of stocks-flows-converters objects which is not provided here but the essential idea is represented by the following equation.
Units	Dollars per cubic metre
Equation	$Recent\ Average\ Sewage\ Fee_t = \left(\sum_{k=t-Horizon}^{t-1} Sewage\ Fee_k\right)/Horizon$ where t is the current time of simulation.
Description	It is the average value of $Sewage\ Fee$ over the most recent time period of $Horizon$ years.
Reference for definition of independent variables	
$Sewage\ Fee$	Object B3.1
$Horizon$	Object B5.6

B5.6 $\boldsymbol{Horizon}$

Type	Converter (constant)
Units	Years
Equation	Not applicable because it is a constant.
Description	It is the time period over which $Recent\ Maximum\ Sewage\ Fee$ is calculated.

B5.7 $\boldsymbol{Annual\ Unused\ Debt\ Capacity}$

Type	Converter
Units	Dollars per year
Equation	$Annual\ Unused\ Debt\ Capacity = Maximum\ Debt\ Capacity/100 \times Average\ Revenue - Debt\ Service$
Description	It is the difference between the maximum allowable debt service charges for the utility and its current actual debt service charges

Reference for definition of independent variables	
$Maximum\ Debt\ Capacity$	Object B5.11
$Average\ Revenue$	Object B5.1
$Debt\ Service$	Object B5.10

B5.8 $\boldsymbol{Maximum\ Fee\ Hike\ Rate}$

Type	Converter (constant)
Units	Percent
Equation	Not applicable because it is a constant
Description	It represents the maximum year-to-year percentage amount by which $Sewage\ Fee$ is allowed to increase.

B5.9 $Current\ Year\ Fee\ Ceiling$

Type	Converter
Units	Dollars per cubic metre
Equation	$Current\ Year\ Fee\ Ceiling = MAX((1 + Maximum\ Fee\ Hike\ Rate/100) \times Last\ Year\ Fee, Recent\ Maximum\ Sewage\ Fee)$
Description	It represents the maximum value which the $Sewage\ Fee$ can attain during a given year. It is the greater of two values: the first one is calculated through increasing the last year's fee by $Maximum\ Fee\ Hike\ Rate$ and the second one is the maximum $Sewage\ Fee$ that has been experienced by the customers over the most recent time period of $Horizon$ years.

Reference for definition of independent variables

$Maximum\ Fee\ Hike\ Rate$	Object B5.8
$Last\ Year\ Fee$	Object B5.3
$Recent\ Maximum\ Sewage\ Fee$	Object B5.4

B5.10 $Debt\ Service$

Type	Converter
Units	Dollars per year
Equation	$Debt\ Service = Principal\ Payment + InterestEx$
Description	It is the annual amount of money used to pay off principal portion of debt and the interest accrued on outstanding amount of debt.
Initial Value	Not applicable

Reference for definition of independent variables

$Principal\ Payment$	Object B3.15
$InterestEx$	Object 0

B5.11 $\boldsymbol{Maximum\ Debt\ Capacity}$

Type	Converter (constant)
Units	Percent
Equation	Not applicable because it is a constant.
Description	A utility may be constrained so as not to issue debt for which $Debt\ Service$ will amount to be more than a certain fraction of its revenue. $Maximum\ Debt\ Capacity$ represents that upper limit for $Debt\ Service$ as a percentage of revenue.

B5.12 $\boldsymbol{Cash\ Used\ Rehab\ 5}$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Used\ Rehab\ 5 = Achievable\ Length\ Rehab\ 5 \times Unit\ Cost\ Rehabilitation[5] \times metre\ to\ km$
Description	It is the portion of cash available for capital works that is utilized for rehabilitating ICG 5 pipes.
Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ 5$	Object B4.14
$Unit\ Cost\ Rehabilitation[5]$	Object B3.36
$metre\ to\ km$	Object B3.34

B5.13 $\boldsymbol{Cash\ Available\ Rehab\ 4}$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Available\ Rehab\ 4 = Cash\ Available\ Cap\ Works - Cash\ Used\ Rehab\ 5$
Description	Amount of cash available that can be used to carry out rehabilitation of ICG 4 pipes.
Reference for definition of independent variables	
$Cash\ Available\ Cap\ Works$	Object B5.14
$Cash\ Used\ Rehab\ 5$	Object B5.12

B5.14 $Cash\ Available\ Cap\ Works$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Available\ Cap\ Works = MAX[0, \{Working\ Capital/DT + Debt\ Issue - (OpEx + Principal\ Payment)\}]$
Description	Total amount of cash available to carry out all planned rehabilitation works.
Reference for definition of independent variables	
$Working\ Capital$	Object B3.5
$Debt\ Issue$	Object B3.14
$OpEx$	Object B3.22
$Principal\ Payment$	Object B3.15

B5.15 $Cash\ Required\ Cap\ Works$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ CapWorks = Cash\ Required\ Rehab\ Grade5 + Cash\ Required\ Rehab\ Grade4$
Description	Total cash requirement per year for all rehabilitation activities.
Reference for definition of independent variables	
$Cash\ Required\ Rehab\ Grade4$	Object B5.19
$Cash\ Required\ Rehab\ Grade5$	Object B5.19

B5.16 $Cash\ Required\ Interest\ Payment$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ Interest\ Payment = InterestEx$
Description	Cash requirement for paying off interest on outstanding debt every year.
Reference for definition of independent variables	
$InterestEx$	Object B3.27

B5.17 *Cash Required MaintenanceEx*

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ MaintenanceEx = \sum_{\boldsymbol{G}=1}^{5} Maintenance\ Expenditure[\boldsymbol{G}]$
Description	Cash requirement on account of maintenance expenditures every year.
Reference for definition of independent variables	
$Maintenance\ Expenditure[\boldsymbol{G}]$	Object B3.30

B5.18 *Cash Required Principal Payment*

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ Principal\ Payment = Annual\ Serials$
Description	Required amount of cash for paying off principal portion of debt in a given year.
Reference for definition of independent variables	
$Annual\ Serials$	Object B3.16

B5.19 *Cash Required Rehab GradeG*

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ Rehab\ Grade\boldsymbol{G} = Target\ Rehab\ Length\ Grade\boldsymbol{G}/metre\ to\ km \times Unit\ Cost\ Rehabilitation[\boldsymbol{G}]$ for $\boldsymbol{G} = 4{,}5$
Description	Cash required per year for rehabilitating the targeted lengths of ICG 4 and 5 pipes.
Reference for definition of independent variables	
$Target\ Rehab\ Length\ Grade\boldsymbol{G}$	Object B4.7 for $\boldsymbol{G} = 4$ Object B4.6 for $\boldsymbol{G} = 5$
$metre\ to\ km$	Object B3.34
$Unit\ Cost\ Rehabilitation[\boldsymbol{G}]$	Object B3.36

B5.20 $Cash\ Required\ WWT\ Ex$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ WWT\ Ex = WWT\ Expenditure$
Description	It is the cash required per year for wastewater treatment.
Reference for definition of independent variables	
$WWT\ Expenditure$	Object B3.31

B5.21 $Cash\ Required$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required = Cash\ Required\ Cap\ Works + Cash\ Required\ Interest\ Payment + Cash\ Required\ MaintenanceEx + Cash\ Required\ Principal\ Payment + Cash\ Required\ WWT\ Ex$
Description	It is the total cash required per year for various expenditure categories.
Reference for definition of independent variables	
$Cash\ Required\ Cap\ Works$	Object B5.15
$Cash\ Required\ Interest\ Payment$	Object B5.16
$Cash\ Required\ MaintenanceEx$	Object B5.17
$Cash\ Required\ Principal\ Payment$	Object B5.18
$Cash\ Required\ WWT\ Ex$	Object B5.20

B5.22 $\boldsymbol{Next\ Year's\ Cash\ Required}$

Type	Converter
Units	Dollars per year.
Equation	$Next\ Year's\ Cash\ Required$ $= Cash\ Required\ Cap\ Works$ $+ Cash\ Required\ Interest\ Payment$ $+ Cash\ Required\ MaintenanceEx$ $+ Cash\ Required\ Principal\ Payment + Cash\ Required\ WWT\ Ex$ $- Fund\ Balance$
Description	It is the sum of cash requirements for various expenditure categories of the utility for the next year.

Reference for definition of independent variables	
$Cash\ Required\ Cap\ Works$	Object B5.15
$Cash\ Required\ Interest\ Payment$	Object B5.16
$Cash\ Required\ MaintenanceEx$	Object B5.17
$Cash\ Required\ Principal\ Payment$	Object B5.18
$Cash\ Required\ WWT\ Ex$	Object B5.20
$Fund\ Balance$	Object B3.19

Appendix C

System dynamics model for management of water distribution networks

C1 Watermains Sector

C1.1 $\boldsymbol{CI\ Pipes\ 0\ to\ 24}$

Type	Stock
Units	Kilometres
Equation	$CI\ Pipes\ 0\ to\ 24(t) = CI\ Pipes\ 0\ to\ 24(t - dt) - CI\ Pipes\ Aging\ to\ 25 \times dt$ where dt is the time step (years) in simulation.
Description	Represents cast iron pipes in the youngest age group (0 to 24 years). It is assumed that no new cast iron pipes are installed, nor the existing (whether cast iron or another material) pipes are replaced with cast iron pipes. Hence, this stock does not have an inflow.

Reference for definition of independent variables	
$CI\ Pipes\ Aging\ to\ 25$	Object C1.2

C1.2 $\boldsymbol{CI\ Pipes\ Aging\ to\ 25}$

Type	Flow
Units	Kilometres per year
Equation	$CI\ Pipes\ Aging\ to\ 25 = CI\ Pipes\ 0\ to\ 24/25$
Description	It represents aging of cast iron pipes. This flow allows pipes to move from stock $CI\ Pipes\ 0\ to\ 24$ to stock $CI\ Pipes\ 25\ to\ 49$.

Reference for definition of independent variables	
$CI\ Pipes\ 0\ to\ 24$	Object C1.1

C1.3 $\boldsymbol{CI\ Pipes\ 25\ to\ 49}$

Type	Stock
Units	Kilometres
Equation	$CI\ Pipes\ 25\ to\ 49(t) = CI\ Pipes\ 25\ to\ 49(t - dt) + (CI\ Pipes\ Aging\ to\ 25 - CI\ Pipes\ Aging\ to\ 50) \times dt$
Description	Represents cast iron pipes in the age group (25 to 49 years).
Reference for definition of independent variables	
$CI\ Pipes\ Aging\ to\ 25$	Object C1.2
$CI\ Pipes\ Aging\ to\ 50$	Object C1.4

C1.4 $\boldsymbol{CI\ Pipes\ Aging\ to\ 50}$

Type	Flow
Units	Kilometres per year
Equation	$CI\ Pipes\ Aging\ to\ 50 = CI\ Pipes\ 25\ to\ 49/25$
Description	It represents aging of cast iron pipes. This flow allows pipes to move from stock $CI\ Pipes\ 25\ to\ 49$ to stock $CI\ Pipes\ 50\ to\ 74$.
Reference for definition of independent variables	
$CI\ Pipes\ 25\ to\ 49$	Object C1.3

C1.5 $\boldsymbol{CI\ Pipes\ 50\ to\ 74}$

Type	Stock
Units	Kilometres
Equation	$CI\ Pipes\ 50\ to\ 74(t) = CI\ Pipes\ 50\ to\ 74(t - dt) + (CI\ Pipes\ Aging\ to\ 50 - CI\ Pipes\ Aging\ to\ 75) \times dt$
Description	Represents cast iron pipes in the age group (50 to 74 years).
Reference for definition of independent variables	
$CI\ Pipes\ Aging\ to\ 50$	Object C1.4
$CI\ Pipes\ Aging\ to\ 75$	Object C1.6

C1.6 $\mathit{CI\ Pipes\ Aging\ to}\ 75$

Type	Flow
Units	Kilometres per year
Equation	$\mathit{CI\ Pipes\ Aging\ to}\ 75 = \mathit{CI\ Pipes}\ 50\ \mathit{to}\ 74/25$
Description	It represents aging of cast iron pipes. This flow allows pipes to move from stock $\mathit{CI\ Pipes}\ 50\ \mathit{to}\ 74$ to stock $\mathit{CI\ Pipes}\ 75\ \mathit{to}\ 99$.
Reference for definition of independent variables	
$\mathit{CI\ Pipes}\ 50\ \mathit{to}\ 74$	Object C1.5

C1.7 $\mathit{CI\ Pipes}\ 75\ \mathit{to}\ 99$

Type	Stock
Units	Kilometres
Equation	$\mathit{CI\ Pipes}\ 75\ \mathit{to}\ 99(t) = \mathit{CI\ Pipes}\ 75\ \mathit{to}\ 99(t - dt) + (\mathit{CI\ Pipes\ Aging\ to}\ 75 - \mathit{CI\ Pipes\ Aging\ to}\ 100 - \mathit{CI\ Pipes}\ 75\ \mathit{to}\ 99\ \mathit{Rehab}) \times dt$
Description	Represents cast iron pipes in the age group (75 to 99 years). This stock has two outflows: $\mathit{CI\ Pipes\ Aging\ to}\ 100$ represents the aging of pipes to the next older age group stock, while $\mathit{CI\ Pipes}\ 75\ \mathit{to}\ 99\ \mathit{Rehab}$ represents the rehabilitation of pipes included in this stock.
Reference for definition of independent variables	
$\mathit{CI\ Pipes\ Aging\ to}\ 75$	Object C1.6
$\mathit{CI\ Pipes\ Aging\ to}\ 100$	Object C1.8
$\mathit{CI\ Pipes}\ 75\ \mathit{to}\ 99\ \mathit{Rehab}$	Object C1.10

C1.8 $\boldsymbol{CI\ Pipes\ Aging\ to\ 100}$

Type	Flow
Units	Kilometres per year
Equation	$CI\ Pipes\ Aging\ to\ 100 = CI\ Pipes\ 75\ to\ 99/25$
Description	It represents aging of cast iron pipes. This flow allows pipes to move from stock $CI\ Pipes\ 75\ to\ 99$ to stock $CI\ Pipes\ above\ 100$.
Reference for definition of independent variables	
$CI\ Pipes\ 75\ to\ 99$	Object C1.7

C1.9 $\boldsymbol{Switch\ CI\ Pipes\ 75\ to\ 99\ Rehab}$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	It is a switch that allows the user to specify whether or not CI pipes in age group (75 to 99 years) are to be rehabilitated? It is assigned a value of either 0 or 1 at the beginning of simulation, which then remains constant throughout the simulation. When $Switch\ CI\ Pipes\ 75\ to\ 99\ Rehab$ is set equal to 0 $\Rightarrow CI\ Pipes\ 75\ to\ 99\ Rehab = 0$ that is CI pipes in age group (75 to 99 years) are not rehabilitated. Conversely, when assigned a value of 1, CI pipes in age group (75 to 99 years) can be rehabilitated provided that pipes are available in $CI\ Pipes\ 75\ to\ 99$ stock to be rehabilitated and also funds are available to carry out such rehabilitation.

C1.10 $\boldsymbol{CI\ Pipes\ 75\ to\ 99\ Rehab}$

Type	Flow
Units	Kilometres per year
Equation	$CI\ Pipes\ 75\ to\ 99\ Rehab$ $= Achievable\ Length\ Rehab\ CI\ Pipes\ 75\ \ to\ 99$ $* Switch\ CI\ Pipes\ 75\ to\ 99\ Rehab$
Description	It represents rehabilitation of cast iron pipes in the stock $CI\ Pipes\ 75\ to\ 99$. It is assumed that cast iron pipes when rehabilitated are replaced with PVC pipes. Hence this flow moves pipes from stock $CI\ Pipes\ 75\ to\ 99$ to stock $PVC\ Pipes\ 0\ to\ 24$.

Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ CI\ Pipes\ 75\ \ to\ 99$	Object C4.29
$Switch\ CI\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.9

C1.11 $\boldsymbol{CI\ Pipes\ above\ 100}$

Type	Stock
Units	Kilometres
Equation	$CI\ Pipes\ above\ 100(t)$ $= CI\ Pipes\ above\ 100(t\ -\ dt)$ $+ (CI\ Pipes\ Aging\ to\ 100 - CI\ Pipes\ above\ 100\ Rehab)\ \times\ dt$
Description	Represents cast iron pipes in the age group (above 100 years). This stock does not have an aging outflow associated with it, the assumption being that cast iron pipes above 100 years old are all treated as similar and not further disaggregation is provided for them.

Reference for definition of independent variables	
$CI\ Pipes\ Aging\ to\ 100$	Object C1.8
$CI\ Pipes\ above\ 100\ Rehab$	Object C1.13

C1.12 $\boldsymbol{Switch\ CI\ Pipes\ above\ 100\ Rehab}$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	It is a switch that allows the user to specify whether or not CI pipes in age group (above 100 years) are to be rehabilitated? It is assigned a value of either 0 or 1 at the beginning of simulation, which then remains constant throughout the simulation. When $Switch\ CI\ Pipes\ above\ 100\ Rehab$ is set equal to 0 $\Rightarrow CI\ Pipes\ above\ 100\ Rehab = 0$ that is CI pipes in age group (above 100 years) are not rehabilitated. Conversely, when assigned a value of 1, CI pipes in age group (above 100 years) can be rehabilitated provided that pipes are available in $CI\ Pipes\ above\ 100$ stock to be rehabilitated and also funds are available to carry out such rehabilitation.

C1.13 $\boldsymbol{CI\ Pipes\ above\ 100\ Rehab}$

Type	Flow
Units	Kilometres per year
Equation	$CI\ Pipes\ above\ 100\ Rehab = Achievable\ Length\ Rehab\ CI\ Pipes\ above\ 100 * Switch\ CI\ Pipes\ above\ 100\ Rehab$
Description	It represents rehabilitation of cast iron pipes in the stock $CI\ Pipes\ above\ 100$. It is assumed that cast iron pipes when rehabilitated are replaced with PVC pipes. Hence this flow moves pipes from stock $CI\ above\ 100$ to stock $PVC\ Pipes\ 0\ to\ 24$.

Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ CI\ Pipes\ above\ 100$	Object C4.27
$Switch\ CI\ Pipes\ above\ 100\ Rehab$	Object C1.12

C1.14 $\boldsymbol{PVC\ Pipes\ 0\ to\ 24}$

Type	Stock
Units	Kilometres
Equation	$PVC\ Pipes\ 0\ to\ 24(t)$ $= PVC\ Pipes\ 0\ to\ 24(t - dt)$ $+ (New\ Pipes\ Installation + CI\ Pipes\ 75\ to\ 99\ Rehab$ $+ CI\ Pipes\ above\ 100\ Rehab + PVC\ Pipes\ 75\ to\ 99\ Rehab$ $+ PVC\ Pipes\ 100\ to\ 124\ Rehab + PVC\ Pipes\ 125\ to\ 149\ Rehab$ $+ PVC\ Pipes\ above\ 150\ Rehab - PVC\ Pipes\ Aging\ to\ 25) \times dt$
Description	Represents PVC pipes in the youngest age group (0 to 24 years). It is assumed that no new cast iron pipes are installed, nor the existing (whether cast iron or another material) pipes are replaced with cast iron pipes. Hence, this stock does not have an inflow.
Reference for definition of independent variables	
$New\ Pipes\ Installation$	Object C1.15
$CI\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.10
$CI\ Pipes\ above\ 100\ Rehab$	Object C1.13
$PVC\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.25
$PVC\ Pipes\ 100\ to\ 124\ Rehab$	Object C1.29
$PVC\ Pipes\ 125\ to\ 149\ Rehab$	Object C1.33
$PVC\ Pipes\ above\ 150\ Rehab$	Object C1.36
$PVC\ Pipes\ Aging\ to\ 25$	Object C1.17

C1.15 $\boldsymbol{New\ Pipes\ Installation}$

Type	Flow
Units	Kilometres per year
Equation	$New\ Pipes\ Installation = Population\ Growth \times Pipes\ to\ Populaion\ Ratio$
Description	This flow represents annual expansion of the network to service growing population.
Reference for definition of independent variables	
$Population\ Growth$	Object C2.10
$Pipes\ to\ Population\ Ratio$	Object C1.16

C1.16 $\boldsymbol{Pipes\ to\ Population\ Ratio}$

Type	Converter
Units	Kilometres per person
Equation	Not applicable as it is assumed constant.
Description	It is the length of pipes to service an additional consumer.

C1.17 $\boldsymbol{PVC\ Pipes\ Aging\ to\ 25}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ Aging\ to\ 25 = PVC\ Pipes\ 0\ to\ 24/25$
Description	It represents aging of PVC pipes. This flow allows pipes to move from stock $PVC\ Pipes\ 0\ to\ 24$ to stock $PVC\ Pipes\ 25\ to\ 49$.

Reference for definition of independent variables	
$PVC\ Pipes\ 0\ to\ 24$	Object C1.14

C1.18 $\boldsymbol{PVC\ Pipes\ 25\ to\ 49}$

Type	Stock
Units	Kilometres
Equation	$PVC\ Pipes\ 25\ to\ 49(t) = PVC\ Pipes\ 25\ to\ 49(t - dt) + (PVC\ Pipes\ Aging\ to\ 25 - PVC\ Pipes\ Aging\ to\ 50) \times dt$
Description	Represents PVC pipes in the age group (25 to 49 years).

Reference for definition of independent variables	
$PVC\ Pipes\ Aging\ to\ 25$	Object C1.17
$PVC\ Pipes\ Aging\ to\ 50$	Object C1.19

C1.19 $\boldsymbol{PVC\ Pipes\ Aging\ to\ 50}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ Aging\ to\ 50 = PVC\ Pipes\ 25\ to\ 49/25$
Description	It represents aging of PVC pipes. This flow allows pipes to move from stock $PVC\ Pipes\ 25\ to\ 49$ to stock $PVC\ Pipes\ 50\ to\ 74$.
Reference for definition of independent variables	
$PVC\ Pipes\ 25\ to\ 49$	Object C1.18

C1.20 $\boldsymbol{PVC\ Pipes\ 50\ to\ 74}$

Type	Stock
Units	Kilometres
Equation	$PVC\ Pipes\ 50\ to\ 74(t) = PVC\ Pipes\ 50\ to\ 74(t - dt) + (PVC\ Pipes\ Aging\ to\ 50 - PVC\ Pipes\ Aging\ to\ 75) \times dt$
Description	Represents PVC pipes in the age group (50 to 74 years).
Reference for definition of independent variables	
$PVC\ Pipes\ Aging\ to\ 50$	Object C1.19
$PVC\ Pipes\ Aging\ to\ 75$	Object C1.21

C1.21 $\boldsymbol{PVC\ Pipes\ Aging\ to\ 75}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ Aging\ to\ 75 = PVC\ Pipes\ 50\ to\ 74/25$
Description	It represents aging of PVC pipes. This flow allows pipes to move from stock $PVC\ Pipes\ 50\ to\ 74$ to stock $PVC\ Pipes\ 75\ to\ 99$.
Reference for definition of independent variables	
$PVC\ Pipes\ 50\ to\ 74$	Object C1.20

C1.22 $\boldsymbol{PVC\ Pipes\ 75\ to\ 99}$

Type	Stock
Units	Kilometres
Equation	$PVC\ Pipes\ 75\ to\ 99(t)$ $= PVC\ Pipes\ 75\ to\ 99(t - dt)$ $+ (PVC\ Pipes\ Aging\ to\ 75 - PVC\ Pipes\ Aging\ to\ 100$ $- PVC\ Pipes\ 75\ to\ 99\ Rehab) \times dt$
Description	Represents PVC pipes in the age group (75 to 99 years). This stock has two outflows: $PVCI\ Pipes\ Aging\ to\ 100$ represents the aging of pipes to the next older age group stock, while $PVC\ Pipes\ 75\ to\ 99\ Rehab$ represents the rehabilitation of pipes included in this stock.

Reference for definition of independent variables	
$PVC\ Pipes\ Aging\ to\ 75$	Object C1.21
$PVC\ Pipes\ Aging\ to\ 100$	Object C1.23
$PVC\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.25

C1.23 $\boldsymbol{PVC\ Pipes\ Aging\ to\ 100}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ Aging\ to\ 100 = PVC\ Pipes\ 75\ to\ 99/25$
Description	It represents aging of PVC pipes. This flow allows pipes to move from stock $PVC\ Pipes\ 75\ to\ 99$ to stock $PVC\ Pipes\ above\ 100$.

Reference for definition of independent variables	
$PVC\ Pipes\ 75\ to\ 99$	Object C1.22

C1.24 $\boldsymbol{Switch\ PVC\ Pipes\ 75\ to\ 99\ Rehab}$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	It is a switch that allows the user to specify whether or not PVC pipes in age group (75 to 99 years) are to be rehabilitated? It is assigned a value of either 0 or 1 at the beginning of simulation, which then remains constant throughout the simulation. When $Switch\ PVC\ Pipes\ 75\ to\ 99\ Rehab$ is set equal to 0 $\Rightarrow PVC\ Pipes\ 75\ to\ 99\ Rehab = 0$ that is PVC pipes in age group (75 to 99 years) are not rehabilitated. Conversely, when assigned a value of 1, PVC pipes in age group (75 to 99 years) can be rehabilitated provided that pipes are available in $PVC\ Pipes\ 75\ to\ 99$ stock to be rehabilitated and also funds are available to carry out such rehabilitation.

C1.25 $\boldsymbol{PVC\ Pipes\ 75\ to\ 99\ Rehab}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ 75\ to\ 99\ Rehab = Achievable\ Length\ Rehab\ PVC\ Pipes\ 75\ \ to\ 99 * Switch\ PVC\ Pipes\ 75\ to\ 99\ Rehab$
Description	It represents rehabilitation of PVC pipes in the stock $PVC\ Pipes\ 75\ to\ 99$.
Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ PVC\ Pipes\ 75\ \ to\ 99$	Object C4.37
$Switch\ PVC\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.24

C1.26 $PVC\ Pipes\ 100\ to\ 124$

Type	Stock
Units	Kilometres
Equation	$PVC\ Pipes\ 100\ to\ 124(t)$ $= PVC\ Pipes\ 100\ to\ 124(t\ -\ dt)$ $+ (PVC\ Pipes\ Aging\ to\ 100 - PVC\ Aging\ to\ 125$ $- PVC\ Pipes\ 100\ to\ 124\ Rehab)\ \times\ dt$
Description	Represents PVC pipes in the age group (100 to 124 years).
Reference for definition of independent variables	
$PVC\ Pipes\ Aging\ to\ 100$	Object C1.23
$PVC\ Pipes\ Aging\ to\ 125$	Object C1.27
$PVC\ Pipes\ 100\ to\ 124\ Rehab$	Object C1.29

C1.27 $PVC\ Pipes\ Aging\ to\ 125$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ Aging\ to\ 125 = PVC\ Pipes\ 100\ to\ 124/25$
Description	It represents aging of PVC pipes. This flow allows pipes to move from stock $PVC\ Pipes\ 100\ to\ 124$ to stock $PVC\ Pipes\ 125\ to\ 149$.
Reference for definition of independent variables	
$PVC\ Pipes\ 100\ to\ 124$	Object C1.26

C1.28 $\boldsymbol{Switch\ PVC\ Pipes\ 100\ to\ 124\ Rehab}$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	It is a switch that allows the user to specify whether or not PVC pipes in age group (100 to 124 years) are to be rehabilitated? It is assigned a value of either 0 or 1 at the beginning of simulation, which then remains constant throughout the simulation. When $Switch\ PVC\ Pipes\ 100\ to\ 124\ Rehab$ is set equal to 0 $\Rightarrow PVC\ Pipes\ 100\ to\ 124\ Rehab = 0$ that is PVC pipes in age group (100 to 124 years) are not rehabilitated. Conversely, when assigned a value of 1, PVC pipes in age group (100 to 124 years) can be rehabilitated provided that pipes are available in $PVC\ Pipes\ 100\ to\ 124$ stock to be rehabilitated and also funds are available to carry out such rehabilitation.

C1.29 $\boldsymbol{PVC\ Pipes\ 100\ to\ 124\ Rehab}$

Type	Flow	
Units	Kilometres per year	
Equation	$PVC\ Pipes\ 100\ to\ 124\ Rehab = Achievable\ Length\ Rehab\ PVC\ Pipes\ 100\ \ to\ 124 * Switch\ PVC\ Pipes\ 100\ to\ 124\ Rehab$	
Description	It represents rehabilitation of PVC pipes in the stock $PVC\ Pipes\ 100\ to\ 124$.	
Reference for definition of independent variables		
$Achievable\ Length\ Rehab\ PVC\ Pipes\ 100\ to\ 124$	Object C4.35	
$Switch\ PVC\ Pipes\ 100\ to\ 124\ Rehab$	Object C1.28	

C1.30 $\boldsymbol{PVC\ Pipes\ 125\ to\ 149}$

Type	Stock
Units	Kilometres
Equation	$PVC\ Pipes\ 125\ to\ 149(t) = PVC\ Pipes\ 125\ to\ 149(t - dt) + (PVC\ Pipes\ Aging\ to\ 125 - PVC\ Aging\ to\ 150 - PVC\ Pipes\ 125\ to\ 149\ Rehab) \times dt$
Description	Represents PVC pipes in the age group (125 to 149 years).
Reference for definition of independent variables	
$PVC\ Pipes\ Aging\ to\ 125$	Object C1.27
$PVC\ Pipes\ Aging\ to\ 150$	Object C1.31
$PVC\ Pipes\ 125\ to\ 149\ Rehab$	Object C1.33

C1.31 $\boldsymbol{PVC\ Pipes\ Aging\ to\ 150}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ Aging\ to\ 150 = PVC\ Pipes\ 125\ to\ 149/25$
Description	It represents aging of PVC pipes. This flow allows pipes to move from stock $PVC\ Pipes\ 125\ to\ 149$ to stock $PVC\ Pipes\ above\ 150$.
Reference for definition of independent variables	
$PVC\ Pipes\ 125\ to\ 149$	Object C1.30

C1.32 $\boldsymbol{Switch\ PVC\ Pipes\ 125\ to\ 149\ Rehab}$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	It is a switch that allows the user to specify whether or not PVC pipes in age group (125 to 149 years) are to be rehabilitated? It is assigned a value of either 0 or 1 at the beginning of simulation, which then remains constant throughout the simulation. When $Switch\ PVC\ Pipes\ 125\ to\ 149\ Rehab$ is set equal to 0 $\Rightarrow PVC\ Pipes\ 125\ to\ 149\ Rehab = 0$ that is PVC pipes in age group (125 to 149 years) are not rehabilitated. Conversely, when assigned a value of 1, PVC pipes in age group (125 to 149 years) can be rehabilitated provided that pipes are available in $PVC\ Pipes\ 125\ to\ 149$ stock to be rehabilitated and also funds are available to carry out such rehabilitation.

C1.33 $\boldsymbol{PVC\ Pipes\ 125\ to\ 149\ Rehab}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ 125\ to\ 149\ Rehab = Achievable\ Length\ Rehab\ PVC\ Pipes\ 125\ to\ 149 * Switch\ PVC\ Pipes\ 125\ to\ 149\ Rehab$
Description	It represents rehabilitation of PVC pipes in the stock $PVC\ Pipes\ 125\ to\ 149$.

Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ PVC\ Pipes\ 125\ to\ 149$	Object C4.33
$Switch\ PVC\ Pipes\ 125\ to\ 149\ Rehab$	Object C1.32

C1.34 $\boldsymbol{PVC\ Pipes\ above\ 150}$

Type	Stock
Units	Kilometres
Equation	$PVC\ Pipes\ above\ 150(t) = PVC\ Pipes\ above\ 150(t - dt) + (PVC\ Pipes\ Aging\ to\ 150 - PVC\ Pipes\ above\ 150\ Rehab) \times dt$
Description	Represents PVC pipes in the age group (above 150 years). This stock does not have an aging outflow associated with it, the assumption being that PVC pipes above 150 years old are all treated as similar and not further disaggregation is provided for them.

Reference for definition of independent variables	
$PVC\ Pipes\ Aging\ to\ 150$	Object C1.31
$PVC\ Pipes\ above\ 150\ Rehab$	Object C1.36

C1.35 $\boldsymbol{Switch\ PVC\ Pipes\ above\ 150\ Rehab}$

Type	Converter (Constant)
Units	Dimensionless
Equation	Not applicable because it is a constant
Description	It is a switch that allows the user to specify whether or not PVC pipes in age group (above 150 years) are to be rehabilitated? It is assigned a value of either 0 or 1 at the beginning of simulation, which then remains constant throughout the simulation. When $Switch\ PVC\ Pipes\ above\ 150\ Rehab$ is set equal to 0 $\Rightarrow PVC\ Pipes\ above\ 150\ Rehab = 0$ that is PVC pipes in age group (above 150 years) are not rehabilitated. Conversely, when assigned a value of 1, PVC pipes in age group (above 150 years) can be rehabilitated provided that pipes are available in $PVC\ Pipes\ above\ 150$ stock to be rehabilitated and also funds are available to carry out such rehabilitation.

C1.36 $\boldsymbol{PVC\ Pipes\ above\ 150\ Rehab}$

Type	Flow
Units	Kilometres per year
Equation	$PVC\ Pipes\ above\ 150\ Rehab = Achievable\ Length\ Rehab\ PVC\ Pipes\ above\ 150 * Switch\ PVC\ Pipes\ above\ 150$
Description	It represents rehabilitation of PVC pipes in the stock $PVC\ Pipes\ above\ 150$.

Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ PVC\ Pipes\ above\ 150$	Object C4.31
$Switch\ PVC\ Pipes\ above\ 150\ Rehab$	Object C1.35

C2 Consumer Sector

C2.1 $\boldsymbol{Water\ Demand}$

Type	Stock
Units	Litres per capita per day
Equation	$Water\ Demand(t) = Water\ Demand(t - dt) - (Price\ Induced\ Reduction) \times DT$
Description	It is the average daily volume of water consumed by a person.

Reference for definition of independent variables	
$Price\ Induced\ Reduction$	Object C2.2

C2.2 $Price\ Induced\ Reduction$

Type	Flow
Units	Litres per capita per day per year
Equation	$Price\ Induced\ Reduction = MIN((Water\ Demand - New\ Water\ Demand)/Demand\ Adjustment\ Period, (Water\ Demand - Minimum\ Demand))$
Description	It is the change in water demand caused by an increase in $Water\ Fee$. 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 $Price\ Induced\ Reduction$ does not cause value of $Water\ Demand$ to fall below its lower limit specified as $Minimum\ Demand$. It should also be noted that the flow $Price\ Induced\ Reduction$ is a unidirectional outflow for stock $Water\ Demand$. This means that $Price\ Induced\ Reduction$ can only assume non-negative values i.e., $Water\ Demand$ can decrease as a result of an increase in $Water\ Fee$ but if there is a decrease in $Water\ Fee$ then the stock $Water\ Demand$ remains unchanged.

Reference for definition of independent variables	
$Water\ Demand$	Object C2.1
$New\ Water\ Demand$	Object C2.3
$Demand\ Adjustment\ Period$	Object C2.8
$Minimum\ Water\ Demand$	Object C2.7

C2.3 $\boldsymbol{New\ Water\ Demand}$

Type	Converter
Units	Litres per capita per day
Equation	$New\ Water\ Demand = INIT(Water\ Demand) - Change\ in\ Water\ Demand$
Description	It is the new value that the stock $Water\ Demand$ is to attain as a result of price induced change in water demand. However, this new value is not attained instantaneously and instead is achieved over a $Demand\ Adjustment\ Period$ as shown in the formulation of $Price\ Induced\ Reduction$. The function $INIT(Water\ Demand)$ returns the initial (start of simulation) value of $Water\ Demand$.
Reference for definition of independent variables	
$Water\ Demand$	Object C2.1
$Change\ in\ Water\ Demand$	Object C2.4

C2.4 $\boldsymbol{Change\ in\ Water\ Demand}$

Type	Converter
Units	Litres per capita per day
Equation	$Change\ in\ Water\ Demand = MAX(Price\ Elasticity \times Fee\ Change\ Real\ Dollars/100 \times Water\ Demand\ ,0)$
Description	It is the change in water demand caused by an increase in water fee. In this study it is assumed that $Water\ Demand$ can only decrease as a result of price increases but does not increase if water fee decreases. Hence, the function $MAX(\ )$ is used so that the change in demand is calculated only as a result of increases in water fee and is considered zero otherwise.
Reference for definition of independent variables	
$Price\ Elasticity$	Object C2.6
$Fee\ Change\ Real\ Dollars$	Object C2.5
$Water\ Demand$	Object C2.1

C2.5 $Fee\ Change\ Real\ Dollars$

Type	Converter
Units	Dimensionless
Equation	$Fee\ Change\ Real\ Dollars = (Water\ Fee \times e^{-CPI/100} - INIT(Water\ Fee))/INIT(Water\ Fee) \times 100$
Description	It is the percentage change in water fee compared to the initial (at $t = 0$) water fee. The function $INIT(Water\ Fee)$ returns the initial (starting) value of $Water\ Fee$. Prevailing value of $Water\ Fee$ is deflated using the consumer price index (CPI) with the assumption that the consumers respond to only real increase in water fee instead of nominal increase.
Reference for definition of independent variables	
$Water\ Fee$	Object C3.1
CPI	Object C5.33

C2.6 $Price\ Elasticity$

Type	Converter (Constant)
Units	Percent/Percent (dimensionless)
Equation	Not applicable because it is a constant
Description	It is equal to the percentage change in $Water\ Demand$ divided by the percentage change in $Water\ Fee$. 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 a user wishes to specify a -0.35 value for the $Price\ Elasticity$ then they simply need to input it as 0.35

C2.7 $Minimum\ Water\ Demand$

Type	Converter (Constant)
Units	Litres per capita per day
Equation	Not applicable because it is a constant.
Description	It is the lower limit imposed on $Water\ Demand$. Hence, the value of $Water\ Demand$ cannot decrease beyond $Minimum\ Demand$. Its value is specified by the user for any simulation scenario and it then remains constant throughout the simulation.

C2.8 $Demand\ Adjustment\ Period$

Type	Converter (Constant)
Units	Years
Equation	Not applicable since it is a constant
Description	It is the time period over which a change in $Water\ Demand$ is implemented.

C2.9 $Population$

Type	Stock
Units	Persons
Equation	$Population(t) = Population(t - dt) + (Population\ Growth) \times DT$
Description	It is the total number of consumers served by the water utility.
Reference for definition of independent variables	
$Population\ Growth$	Object C2.10

C2.10 $Population\ Growth$

Type	Flow
Units	Persons per year
Equation	$Population\ Growth = Population * Population\ Growth\ Rate/100$
Description	It represents the annual increase in the population served by the water utility. It should be noted that this flow is bi-directional that is it can add to as well as subtract from the stock $Population$. The decline in population occurs when the $Population\ Growth\ Rate$ is set to a negative value and represents communities with shrinking population base (e.g. ‘rust belt’ cities).
Reference for definition of independent variables	
$Population$	Object C2.9
$Population\ Growth\ Rate$	Object C2.11

C2.11 $Population\ Growth\ Rate$

Type	Converter
Units	Percent per year
Equation	Not applicable since it is a constant.
Description	The user specifies its value at the start of simulation which then remains constant throughout the simulation. As noted in the description of $Population\ Growth$, this parameter can be assigned both positive and negative values.

C2.12 $Annual\ Median\ Household\ Income$

Type	Converter
Units	Dollars
Equation	Not applicable since it is a constant.
Description	It is the annual median household income of the population served by the utility. The user specifies its value at the start of simulation which then remains constant throughout the simulation.

C2.13 $Inflated\ Annual\ Household\ Income$

Type	Converter
Units	Dollars per year
Equation	$Inflated\ Household\ Income = Annual\ Median\ Household\ Income \times e^{CPI/100 \times TIME}$
Description	$Annual\ Median\ Household\ Income$ is inflated based on the assumption that the average income grows at the annual inflation rate of CPI. $TIME$ is the time elapsed since the start of simulation.
Reference for definition of independent variables	
$Annual\ Median\ Household\ Income$	Object C2.12
CPI	Object C5.33

C2.14 $Average\ Household\ Size$

Type	Converter
Units	Persons
Equation	Not applicable since it is a constant.
Description	The average number of persons per household for the population served by the utility. The user specifies its value at the start of simulation which then remains constant throughout the simulation.

C2.15 $Annual\ Household\ Consumption$

Type	Converter
Units	Cubic metres per year
Equation	$Annual\ Household\ Consumption = Water\ Demand \times Average\ Household\ Size \times 365/1000$
Description	It is the annual volume of water consumed by an average household.
Reference for definition of independent variables	
$Water\ Demand$	Object C2.1
$Average\ Household\ Size$	Object C2.14

C2.16 *Annual Household Bill*

Type	Converter
Units	Dollar per year
Equation	$Annual\ Household\ Bill = Annual\ Household\ Consumption \times Water\ Fee$
Description	The annual water bill paid by an average household.
Reference for definition of independent variables	
Annual Household Consumption	Object C2.15
Water Fee	Object C3.1

C2.17 *Water Bill Burden*

Type	Converter
Units	Percent
Equation	$Water\ Bill\ Burden = Annual\ Household\ Bill / Inflated\ Household\ Income \times 100$
Description	It is the fraction of household income spent on water consumption.
Reference for definition of independent variables	
Annual Household Bill	Object C2.16
Inflated Household Income	Object C2.13

C2.18 *Water Bill Hardship Threshold*

Type	Converter
Units	Percentage
Equation	Not applicable since it is a constant.
Description	If *Water Bill Burden* is greater than *Water Bill Hardship Threshold* (percentage of a household's income) then water fee is assumed to be not affordable. User specifies its value at the start of simulation which then remains constant throughout the simulation.

C2.19 $\boldsymbol{Fee\ Hike\ Financial\ Burden\ Acceptability}$

Type	Converter
Units	Percent
Equation	$Fee\ Hike\ Financial\ Burden\ Acceptability = GRAPH(Water\ Bill\ Burden)\ (0.00,100),(0.15,99.5),(0.3,99.0),(0.45,97.0),(0.6,93.5),(0.75,86.5),(0.9,78.0),(1.05,65.0),(1.2,46.5),(1.35,22.5),(1.5,0.00)$
Description	It is the percentage of fee hike acceptable to consumers. It is modelled as a graph function of $Water\ Bill\ Burden$ as the independent variable. The coordinates given in the above equation show the curve used as a default in the model. The abscissa in each point represent the independent variable $Water\ Bill\ Burden$ while the ordinate represents the dependent variable $Fee\ Hike\ Financial\ Burden\ Acceptability$. For example, $(0.75,86.5)$ implies that if $Water\ Bill\ Burden$ is 0.75% of the household income, then consumers will be willing to accept only 86.5% of a proposed fee increase. User can replace the default function using a graphical input functionality at the user interface level of the model. If the user wishes to switch off this function, then this can simply be done by assigning a value of 100 (%) to each ordinate in the graph.
Reference for definition of independent variables	
$Water\ Bill\ Burden$	Object C2.17

C2.20 $Fee\ Hike\ Service\ Level\ Acceptability$

Type	Converter
Units	Percent
Equation	$Fee\ Hike\ Service\ Level\ Acceptability$ $= GRAPH(Fraction\ Hi\ Deter\ Pipes)$ $(0.00{,}0.00), (2.00{,}0.00), (4.00{,}1.00), (6.00{,}2.00), (8.00{,}3.50), (10.00{,}5.50), (12.0{,}9.50), (14.00{,}17.00), (16.00{,}32.00), (18.00{,}60.5), (20.00{,}100.00)$
Description	It is the percentage increase in consumers' willingness to accept proposed fee hikes. The increased in willingness is hypothesized to be driven by consumers' dissatisfaction with prevailing level of service as measured by the fraction of highly deteriorated pipes in the network. It is assumed that as the service level becomes poor, consumers become more willing to accept increase in water fee with an expectation that the higher fee will ultimately help improve the service performance of the network. This function is modelled as a graph function with $Fraction\ Hi\ Deter\ Pipes$ as the independent variable. The coordinates given in the above equation show the curve used as a default in the model. The abscissa in each point represent the independent variable $Fraction\ Hi\ Deter\ Pipes$ while the ordinate represents the dependent variable $Fee\ Hike\ Service\ Level\ Acceptability$. For example, $(10.00{,}5.50)$ implies that if 10% of the network is in highly deteriorated condition, then consumers' willingness to accept a proposed fee hike will increase by 5.5%. Users can replace the default function using a graphical input functionality at the user interface level of the model. If the user wishes to switch off this function, then this can simply be done by assigning a value of 0 (%) to each ordinate in the graph.

Reference for definition of independent variables	
$Fraction\ Hi\ Deter\ Pipes$	Object C4.9

C2.21 $\boldsymbol{Consumers\ Fee\ Hike\ Acceptability}$

Type	Converter
Units	Cubic metres per year
Equation	$Consumers\ Fee\ Hike\ Acceptability$ $= MIN(Fee\ Hike\ Financial\ Burden\ Acceptability$ $\times (1 + Fee\ Hike\ Service\ Level\ Acceptability/100), 100)$
Description	This object combines the effect of consumers' willingness to accept proposed fee hikes due to financial and service performance considerations. The function $MIN(\quad)$ is used so that the acceptable fee hike is not greater than the proposed fee hike.

Reference for definition of independent variables	
$Fee\ Hike\ Financial\ Burden\ Acceptability$	Object C2.19
$Fee\ Hike\ Service\ Level\ Acceptability$	Object C2.20

C2.22 $\boldsymbol{Maximum\ Fee\ Hike\ Rate}$

Type	Converter (constant)
Units	Percent per year
Equation	Not applicable because it is a constant
Description	It represents the maximum year-to-year percentage amount beyond which $Water\ Fee$ is preferred not to be increases. Its value is specified by the user.

C2.23 $\boldsymbol{Maximum\ Acceptable\ Fraction\ Hi\ Deter\ Pipes}$

Type	Converter (constant)
Units	Percentage of network.
Equation	Not applicable because it is a constant
Description	It is the percentage of network that the user specifies at the start of simulation. If the fraction of highly deteriorated pipes in the network exceeds this maximum allowable limit then $Effective\ Rehab\ Rate$ (Object C4.14) no longer remains equal to $Preferred\ Rehab\ Rate$ (Object C4.13) and assumes a value equal to the $Rehab\ Rate$. It can be assigned any value between 0 to 100% (both inclusive).

C2.24 $\mathit{Water\ Consumed}$

Type	Stock
Units	Cubic metres
Equation	$\mathit{Water\ Consumed}(t) = \mathit{Water\ Consumed}(t - dt) + (\mathit{Annual\ Water\ Consumption}) \times DT$
Description	It is the cumulative volume of water consumed since the beginning of the simulation.
Reference for definition of independent variables	
$\mathit{Annual\ Water\ Consumption}$	Object C2.25

C2.25 $\mathit{Annual\ Water\ Consumption}$

Type	Flow
Units	Cubic metres per year
Equation	$\mathit{Annual\ Water\ Consumption} = \mathit{Water\ Demand} \times \mathit{Population} \times 365/1000$
Description	This flow represents the annual volume of water consumption.
Reference for definition of independent variables	
$\mathit{Water\ Demand}$	Object C2.1
$\mathit{Population}$	Object C2.9

C3 Finance Sector

C3.1 $\boldsymbol{Water\ Fee}$

Type	Stock
Units	Dollars per cubic metre
Equation	$Water\ Fee(t) = Water\_Fee(t - dt) + (Water\ Fee\ Hike - Water\ Fee\ Decline) \times dt$
Description	It is the amount (dollars) that the utility charges its customers for every cubic metre of consumed by customers. In this study a constant volumetric $Water\ Fee$ is assumed. This means that customers pay the same price for each cubic metre of sewage regardless of their total consumption levels.

Reference for definition of independent variables	
$Water\ Fee\ Hike$	Object C3.2
$Water\ Fee\ Decline$	Object C3.3

C3.2 $\boldsymbol{Water\ Fee\ Hike}$

Type	Flow
Units	Dollars per cubic metre per year
Equation	$Water\ Fee\ Hike = New\ Water\ Fee - Water\ Fee$
Description	It is the annual increase in $Water\ Fee$.

Reference for definition of independent variables	
$New\ Water\ Fee$	Object C5.56
$Water\ Fee$	Object C3.1

C3.3 $Water\ Fee\ Decline$

Type	Flow
Units	Dollars per cubic metre per year
Equation	$Water\ Fee\ Decline = IF\ (Fund\ Balance < Desired\ Fund\ Reserve)\ OR\ (Water\ Fee < New\ Water\ Fee)\ THEN\ 0\ ELSE\ MIN\big((Water\ Fee - 0.01), (Water\ Fee - New\ Water\ Fee)\big)$
Description	This flow is used to decrease the value of $Water\ Fee$. But this decrease is not implemented if the current value of $Water\ Fee$ is already below the desired value of $New\ Water\ Fee$ or the utility's current positive surplus $Fund\ Balance$ is below its $Desired\ Fund\ Reserve$ level. However, when the utility already has a reserve balance of at least equal to $Desired\ Fund\ Reserve$ and its other cash requirements can be met with a $New\ Water\ Fee$ that is less than the current $Water\ Fee$, then $Water\ Fee$ is allowed to decrease. The function $MIN(\quad)$ is used to ensure that the $Water\ Fee$ can decrease upto $New\ Water\ Fee$ but not below 1 cent ($0.01) per cubic metre.

Reference for definition of independent variables	
$Fund\ Balance$	Object C3.15
$Desired\ Fund\ Reserve$	Object C5.46
$Water\ Fee$	Object C3.1
$New\ Water\ Fee$	Object C5.56

C3.4 $Working\ Capital$

Type	Stock
Units	Dollars
Equation	$Working\ Capital(t) = Working\ Capital(t - dt) + (Cash\ Inflow - Cash\ Outflow) \times DT$
Description	It is the cash at hand with the utility.
Reference for definition of independent variables	
$Cash\ Inflow$	Object C3.5
$Cash\ Outflow$	Object C3.6

C3.5 $Cash\ Inflow$

Type	Flow
Units	Dollars per year
Equation	$Cash\ Inflow = Annual\ Income + Debt\ Issue$
Description	Annual amount of cash received by the water utility.
Reference for definition of independent variables	
$Annual\ Income$	Object C3.7
$Debt\ Issue$	Object C3.10

C3.6 $Cash\ Outflow$

Type	Flow
Units	Dollars per year
Equation	$Cash\ Outflow = Annual\ Expenditure + Principal\ Payment$
Description	Annual amount of cash paid out by the water utility.
Reference for definition of independent variables	
$Annual\ Expenditure$	Object C3.8
$Principal\ Payment$	Object C3.11

C3.7 $Annual\ Income$

Type	Converter
Units	Dollars per year
Equation	$Annual\ Income = Revenue + Interest\ Earnings$
Description	Annual income for the utility through water fee (revenue) and interest accrued on savings.

Reference for definition of independent variables	
$Revenue$	Object C3.16
$Interest\ Earnings$	Object C3.17

C3.8 $Annual\ Expenditure$

Type	Converter
Units	Dollars per yearr
Equation	$Annual\ Expenditure = OpEx + CapEx$
Description	It is the total annual expenditure incurred by the utility.
$OpEx$	Object C3.18
$CapEx$	Object C3.19

C3.9 $Debt$

Type	Stock
Units	Dollars
Equation	$Debt(t) = Debt(t - dt) + (Debt\_Issue - Principal\_Payment) \times DT$
Description	It represents the total amount of debt carried by the utility at any time during the simulation.

Reference for definition of independent variables	
$Debt\ Issue$	Object C3.10
$Principal\ Payment$	Object C3.11

C3.10 $\boldsymbol{Debt\ Issue}$

Type	Flow
Units	Dollars per year
Equation	$Debt\ Issue = MIN((Current\ Cash\ Required - Working\ Capital/DT), Debt\ Available\ For\ Issue)$
Description	It represents new debt issued by the utility which adds to the existing $Debt$ level.
Reference for definition of independent variables	
$Current\ Cash\ Required$	Object C5.44
$Working\ Capital$	Object C3.4
$Debt\ Available\ For\ Issue$	Object C3.21

C3.11 $\boldsymbol{Principal\ Payment}$

Type	Flow
Units	Dollars per year
Equation	$Principal\ Payment = Annual\ Serials$
Description	When $Debt > 0$, then each year a portion of the outstanding principal amount is paid off and hence reduces $Debt$ level.
Reference for definition of independent variables	
$Annual\ Serials$	Object C3.12

C3.12 $\boldsymbol{Annual\ Serials}$

Type	Stock
Units	Dollars per year
Equation	$Annual\ Serials(t) = Annual\ Serials(t - dt) + (Serial\ Launch - Serial\ Retirement) \times DT$
Description	It is the sum of all serials for outstanding debts issued that is required to be repaid every year until the debt for which the respective serials were issued is fully paid off.

Reference for definition of independent variables	
$Serial\ Launch$	Object C3.13
$Serial\ Retirement$	Object C3.14

C3.13 $\boldsymbol{Serial\ Launch}$

Type	Flow
Units	(Dollars per year) per year
Equation	$Serial\ Launch = Debt\ Issue/Amortization\ Period$
Description	In this study it is assumed that any long term debt that the utility takes on is to be paid off over the $Amortization\ Period$ in such a manner that the principal amount is repaid in equal annual installments plus interest on the outstanding portion of the principal. $Serial\ Launch$ represents that equal annual installment of principal repayment. Whenever a new debt is issued, a corresponding $Serial\ Launch$ is calculated for that debt and is stored in the $Annual\ Serials$ stock for the duration of $Amortization\ Period$.

Reference for definition of independent variables	
$Debt\ Issue$	Object C3.10
$Amortization\ Period$	Object C3.20

C3.14 $Serial\ Retirement$

Type	Flow
Units	(Dollars per year) per year
Equation	$Serial\ Retirement_t = Serial\ Launch_{(t-Amortization\_Period)}$ where t is the prevailing simulation time (years).
Description	As mentioned in description of $Serial\ Launch$, a serial for each new debt is calculated and stored in the stock $Annual\ Serials$. After remaining there for a duration of $Amortization\ Period$, the serial is then removed whence the corresponding debt acquired has been paid off. $Serial\ Retirement$ represents this removal of a serial corresponding to the paid off debt.

Reference for definition of independent variables	
$Serial\ Launch$	Object C3.13
$Amortization\ Period$	Object C3.20

C3.15 $Fund\ Balance$

Type	Stock
Units	Dollars
Equation	$Fund\ Balance(t)$ $= Funds\ Balance(t - dt) + (Revenue$ $+ Interest\ Earnings - OpEx - CapEx) \times DT$
Description	Represents the utility's funds balance.

Reference for definition of independent variables	
$Revenue$	Object C3.16
$Interest\ Earnings$	Object C3.17
$OpEx$	Object C3.18
$CapEx$	Object C3.19

C3.16 $Revenue$

Type	Flow
Units	Dollars per year
Equation	$Revenue = Water\ Fee \times Annual\ Water\ Consumption$
Description	Represents the utility's income derived from charging water fee to the water volume consumed by customers.
Reference for definition of independent variables	
$Water\ Fee$	Object C3.1
$Annual\ Water\ Consumption$	Object C2.25

C3.17 $Interest\ Earnings$

Type	Flow
Units	Dollars per year
Equation	$Interest\ Earnings = Savings\ Rate/100 * \ MAX(0, Fund\ Balance)$
Description	Represents the utility's income derived from interest earned on positive fund balance.
Reference for definition of independent variables	
$Savings\ Rate$	Object C5.32
$Fund\ Balance$	Object C3.15

C3.18 $\boldsymbol{OpEx}$

Type	Flow
Units	Dollars per year
Equation	$OpEx = Water\ Purchase\ Ex + Maintenance\ Ex + Interest\ Ex$
Description	$OpEx$ or operational expenditures are the annual costs associated with management of network (administrative and government overheads), maintenance activities (flushing and minor repairs) and emergency expenditures (watermain breaks, etc), treatment and pumping of wastewater, and interest expenses on borrowed funds.

Reference for definition of independent variables	
$Maintenance\ Ex$	Object C5.26
$Water\ Purchase\ Ex$	Object C5.30
$Interest\ Ex$	Object C3.22

C3.19 $\boldsymbol{CapEx}$

Type	Flow
Units	Dollars per year
Equation	$CapEx = \sum_{\boldsymbol{CapActivity}} CapEx\ byActivity[\boldsymbol{CapActivity}]$ where $\boldsymbol{CapActivity} = AG75to99, AG100to124, AG125to149, AG150to174.$
Description	It is the annual total cost of rehabilitating pipes in various groups.

Reference for definition of independent variables	
$CapEx\ byActivity[\boldsymbol{CapActivity}]$	Object C5.36

C3.20 $\boldsymbol{Amortization\ Period}$

Type	Converter (constant)
Units	Years
Equation	Not applicable because it is a constant.
Description	It is the time period over which the utility pays off a long term debt.

C3.21 $\boldsymbol{Debt\ Available\ For\ Issue}$

Type	Converter
Units	Dollars
Equation	$Debt\ Available\ For\ Issue = MAX(Annual\ Unused\ Debt\ Capacity \times Amortization\ Period, 0)$
Description	Municipal governments are limited in the amount of debt that they can assume e.g., by provincial regulations in the Province of Ontario. This converter calculates the additional amount that the utility can borrow after taking into account its existing debt.

Reference for definition of independent variables	
$Annual\ Unused\ Debt\ Capacity$	Object C5.4
$Amortization\ Period$	Object C3.20

C3.22 $\boldsymbol{Interest\ Ex}$

Type	Converter
Units	Dollars per year
Equation	$Interest\ Ex = Borrowing\ Rate/100 * Debt$
Description	It is the annual interest paid by the utility on its outstanding debt during a given year.

Reference for definition of independent variables	
$Borrowing\ Rate$	Object C5.31
$Debt$	Object C3.9

C4 Watermains Auxiliary Sector

C4.1 $\boldsymbol{WaterMains\ Lengths}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC;

and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$

Type	Converter
Units	Kilometres
Equation	$WaterMains\ Lengths[CI, Age0to24] = CI\ Pipes\ 0\ to\ 24$ $WaterMains\ Lengths[CI, Age25to49] = CI\ Pipes\ 25\ to\ 49$ $WaterMains\ Lengths[CI, Age50to74] = CI\ Pipes\ 50\ to\ 74$ $WaterMains\ Lengths[CI, Age75to99] = CI\ Pipes\ 75\ to\ 99$ $WaterMains\ Lengths[CI, Age100to124] = CI\ Pipes\ above\ 100$ $WaterMains\ Lengths[CI, Age125to149] = 0$ $WaterMains\ Lengths[CI, Age150to174] = 0$ $WaterMains\ Lengths[PVC, Age0to24] = PVC\ Pipes\ 0\ to\ 24$ $WaterMains\ Lengths[PVC, Age25to49] = PVC\ Pipes\ 25\ to\ 49$ $WaterMains\ Lengths[PVC, Age50to74] = PVC\ Pipes\ 50\ to\ 74$ $WaterMains\ Lengths[PVC, Age75to99] = PVC\ Pipes\ 75\ to\ 99$ $WaterMains\ Lengths[PVC, Age100to124] = PVC\ Pipes\ 100\ to\ 124$ $WaterMains\ Lengths[PVC, Age125to149] = PVC\ Pipes\ 120\ to\ 149$ $WaterMains\ Lengths[PVC, Age150to174] = PVC\ Pipes\ above\ 150$
Description	This arrayed object simply stores the values of pipe lengths for both pipe materials and in all age groups. It should be noted that both $WaterMains\ Lengths[CI, Age125to149]$ and $WaterMains\ Lengths[CI, Age150to174]$ are assigned a value of zero because no stocks are included in the model for CI pipes in age groups above 124 years.

Reference for definition of independent variables	
$CI\ Pipes\ 0\ to\ 24$	Object C1.1
$CI\ Pipes\ 25\ to\ 49$	Object C1.3
$CI\ Pipes\ 50\ to\ 74$	Object C1.5
$CI\ Pipes\ 75\ to\ 99$	Object C1.7
$CI\ Pipes\ above\ 100$	Object C1.11

$PVC\ Pipes\ 0\ to\ 24$	Object C1.14
$PVC\ Pipes\ 25\ to\ 49$	Object C1.18
$PVC\ Pipes\ 50\ to\ 74$	Object C1.20
$PVC\ Pipes\ 75\ to\ 99$	Object C1.22
$PVC\ Pipes\ 100\ to\ 124$	Object C1.26
$PVC\ Pipes\ 120\ to\ 149$	Object C1.30
$PVC\ Pipes\ above\ 150$	Object C1.34

C4.2 $\boldsymbol{Total\ Network\ Length}$

Type	Converter
Units	Kilometres
Equation	$Total\ Network\ Length$ $= \sum_{\boldsymbol{MainMat}} \sum_{\boldsymbol{AgeGroups}} WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ where $\boldsymbol{MainMat} = CI, PVC$ $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149, 150\ to\ 174$
Description	It is the total length of pipes in the network.
Reference for definition of independent variables	
$WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.1

C4.3 $\boldsymbol{Average\ Age\ for\ Age\ Groups}[\boldsymbol{AgeGroups}]$

where $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$

Type	Converter
Units	Years
Equation	$Average\ Age\ for\ Age\ Groups[Age0to24] = 12$ $Average\ Age\ for\ Age\ Groups[Age25to49] = 37$ $Average\ Age\ for\ Age\ Groups[Age50to74] = 62$ $Average\ Age\ for\ Age\ Groups[Age75to99] = 87$ $Average\ Age\ for\ Age\ Groups[Age100to124] = 112$ $Average\ Age\ for\ Age\ Groups[Age125to149] = 137$ $Average\ Age\ for\ Age\ Groups[Age150to174] = 162$
Description	This object assigns an average to pipes in different age groups.

C4.4 $\boldsymbol{Average\ Age\ Network}$

Type	Converter
Units	Kilometres
Equation	$Average\ Age\ Network$ $= \sum_{\boldsymbol{AgeGroups}} \left\{ \left(\sum_{\boldsymbol{MainMat}} WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}] \right) \times Average\ Age\ for\ Age\ Groups[\boldsymbol{AgeGroups}] \right\} / Total\ Network\ Length$ for $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149, 150\ to\ 174$ and $\boldsymbol{MainMat} = CI, PVC$
Description	It is the weighted average age of the network.

Reference for definition of independent variables

$WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.1
$Average\ Age\ for\ Age\ Groups[\boldsymbol{AgeGroups}]$	Object C4.3
$Total\ Network\ Length$	Object C4.2

C4.5 $\boldsymbol{AverageAge\ byMaterial}[\boldsymbol{MainMat}]$

where $\boldsymbol{MainMat} = CI$ and PVC

Type	Converter
Units	Years
Equation	$AverageAge\ byMaterial[\boldsymbol{MainMat}] = \sum_{\boldsymbol{AgeGroups}} (WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}] \times Average\ Age\ for\ Age\ Groups[\boldsymbol{AgeGroups}]) / Total\ Network\ Length$ for $\boldsymbol{MainMat} = CI$ and PVC where $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149, 150\ to\ 174$
Description	It is the weighted average age for pipes of each material $\boldsymbol{MainMat}$ where $\boldsymbol{MainMat} = CI$ and PVC.

Reference for definition of independent variables	
$WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.1
$Average\ Age\ for\ Age\ Groups[\boldsymbol{AgeGroups}]$	Object C4.3
$Total\ Network\ Length$	Object C4.2

C4.6 $\boldsymbol{Pipe\ Fractions\ by\ Material}\&\boldsymbol{Age}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC; and

$\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$

Type	Converter	
Units	Dimensionless (Percentage)	
Equation	$Pipe\ Fractions\ by\ Material\&Age[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $= WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $/Total\ Network\ Length \times 100$ for $\boldsymbol{MainMat} = CI$ and PVC $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$	
Description	It is the fraction of each material in each age groups as a percentage of the total network length.	
Reference for definition of independent variables		
$WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.1	
$Total\ Network\ Length$	Object C4.2	

C4.7 $\boldsymbol{Network\ Fractions\ by\ Material}[\boldsymbol{MainMat}]$

where $\boldsymbol{MainMat} = CI$ and PVC

Type	Converter
Units	Dimensionless (Percentage)
Equation	$Network\ Fractions\ by\ Material[\boldsymbol{MainMat}]$ $= \sum_{AgeGroups} WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $/Total\ Network\ Length \times 100$ for $\boldsymbol{MainMat} = CI$ and PVC where $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149, 150\ to\ 174$
Description	It is the fraction of the network made up of pipe material $\boldsymbol{MainMat}$ where $\boldsymbol{MainMat} = CI$ and PVC.

Reference for definition of independent variables	
$WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.1
$Total\ Network\ Length$	Object C4.2

C4.8 $\boldsymbol{Pipe\ Fractions\ by\ Age}[\boldsymbol{AgeGroups}]$

where $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$

Type	Converter
Units	Dimensionless (Percentage)
Equation	$Pipe\ Fractions\ by\ Age[\boldsymbol{AgeGroups}]$ $= \sum_{MainMat} Pipe\ Fractions\ by\ Material\&Age[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $/Total\ Network\ Length \times 100$ for $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$ where $\boldsymbol{MainMat} = CI, PVC$
Description	It is the fraction of the network in each age group $\boldsymbol{AgeGroups}$ where $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$

Reference for definition of independent variables	
$Pipe\ Fractions\ by\ Material\&Age[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.6
$Total\ Network\ Length$	Object C4.2

C4.9 $Fraction\ Hi\ Deter\ Pipes$

Type	Converter
Units	Dimensionless (Percentage)
Equation	$Fraction\ Hi\ Deter\ Pipes$ $= Pipe\ Fractions\ by\ Material\&Age[CI, Age75to99]$ $+ Pipe\ Fractions\ by\ Material\&Age[CI, Age100to124]$ $+ Pipe\ Fractions\ by\ Material\&Age[PVC, Age100to124]$ $+ Pipe\ Fractions\ by\ Material\&Age[PVC, Age125to149]$ $+ Pipe\ Fractions\ by\ Material\&Age[PVC, Age150to174]$
Description	It is the fraction of the network that is in highly deteriorated state. Pipes for which the expected number of breaks exceeds a certain maximum threshold are designated as highly deteriorated pipes. The above equation is based on the assumption that CI pipes older than 75 years of age and PVC pipes older than 100 years are highly deteriorated.

Reference for definition of independent variables	
$Pipe\ Fractions\ by\ Material\&Age[CI, Age75to99]$	Object C4.6
$Pipe\ Fractions\ by\ Material\&Age[CI, Age100to124]$	Object C4.6
$Pipe\ Fractions\ by\ Material\&Age[PVC, Age100to124]$	Object C4.6
$Pipe\ Fractions\ by\ Material\&Age[PVC, Age125to149]$	Object C4.6
$Pipe\ Fractions\ by\ Material\&Age[PVC, Age150to174]$	Object C4.6

C4.10 $Hi\ Deter\ Pipes\ Elimination\ Period$

Type	Converter (constant)
Units	Years
Equation	Not applicable because it is a constant.
Description	When the value of $Fraction\ Hi\ Deter\ Pipes$ exceeds $Maximum\ Acceptable\ Fraction\ Hi\ Deter\ Pipes$, then the model calculates a new value ($Rehab\ Rate$) such that $Fraction\ Hi\ Deter\ Pipes$ is eliminated over a period of $Hi\ Deter\ Pipes\ Elimination\ Period$ years. The value for this elimination period is specified by the user and can range anywhere from 1 to 100 years (both inclusive).

C4.11 $Hi\ Deter\ Pipes\ Exceedance\ Flag$

Type	The actual implementation for this variable in the model consists of a stock-flow-converter structure which is not shown here but the essential idea is represented through the equation given below.
Units	Dimensionless
Equation	$Hi\ Deter\ Pipes\ Exceedance\ Flag = IF\ (Fraction\ Hi\ Deter\ Pipes > Maximum\ Acceptable\ Fraction\ Hi\ Deter\ Pipes)\ THEN\ 1\ ELSE\ 0$
Description	This is a switch which is turned on (assumes a value of 1) as soon as $Fraction\ Hi\ Deter\ Pipes$ becomes greater than the $Maximum\ Acceptable\ Fraction\ Hi\ Deter\ Pipes$. It is important to note that $Hi\ Deter\ Pipes\ Exceedance\ Flag$ does not turn off (becomes zero) when $Fraction\ Hi\ Deter\ Pipes$ again falls below $Maximum\ Acceptable\ Fraction\ Hi\ Deter\ Pipes$ and instead once turned on, it stays that way until $Fraction\ Hi\ Deter\ Pipes$ has become less than a tolerance limit. This formulation is achieved in the model with the help of a stock/flow/converter structure which is not completely represented by the above equation. The idea for such a formulation is that once there is a 'wake-up' call due to the $Fraction\ Hi\ Deter\ Pipes$ exceeding the maximum allowable limit, the utility embarks upon an aggressive rehabilitation program to fix the problem. This aggressive program is aimed toward eliminating the highly deteriorated pipes and once started, it continues until the highly deteriorated pipes fraction has been reduced to a tolerable limit (e.g. 1% of network) and not simply to a value below the maximum acceptable fraction of highly deteriorated pipes.
Reference for definition of independent variables	
$Fraction\ Hi\ Deter\ Pipes$	Object C4.9
$Maximum\ Acceptable\ Fraction\ Hi\ Deter\ Pipes$	Object C2.23

C4.12 $Rehab\ Rate$

Type	In the model this variable is calculated using a combination of stocks-flows-converters objects which is not provided here but the essential idea is represented by the following equation.
Units	Percentage of network per year
Equation	$Rehab\ Rate = Fraction\ Hi\ Deter\ Pipes/Hi\ Deter\ Pipes\ Elimination\ Period$ subject to the condition: $Rehab\ Rate_t = MAX(Rehab\ Rate_{t-1} + Rehab\ Rate_t)$ where t is the current simulation time.
Description	This rehabilitation rate is calculated with the goal of eliminating $Fraction\ Hi\ Deter\ Pipes$ within a time period equal to $Hi\ Deter\ Pipes\ Elimination\ Period$. The constraint shown above is employed so that $Rehab\ Rate$ does not start decreasing with decreasing value of $Fraction\ Hi\ Deter\ Pipes$ and is instead maintained at its maximum value until $Fraction\ Hi\ Deter\ Pipes$ has been reduced below a tolerable limit.
Reference for definition of independent variables	
$Fraction\ Hi\ Deter\ Pipes$	Object C4.9
$Hi\ Deter\ Pipes\ Elimination\ Period$	Object C4.10

C4.13 $Preferred\ Rehab\ Rate$

Type	Converter
Units	Percent per year
Equation	Not applicable (is a constant)
Description	This is a user specified value for the percentage of network to be rehabilitated annually.

C4.14 $\boldsymbol{Effective\ Rehab\ Rate}$

Type	Converter
Units	Percent per year
Equation	$Effective\ Rehab\ Rate = MAX(Preferred\ Rehab\ Rate, Rehab\ Rate)$
Description	The planned rehabilitation rate for next year can be different than the user specified $Preferred\ Rehab\ Rate$. The above equation adopts the larger value between the user specified $Preferred\ Rehab\ Rate$ and model determined $Rehab\ Rate$.
Reference for definition of independent variables	
$Preferred\ Rehab\ Rate$	Object C4.13
$Rehab\ Rate$	Object C4.12

C4.15 $\boldsymbol{Desired\ Rehab\ Length}$

Type	Converter
Units	Kilometresr
Equation	$Desired\ Rehab\ Length = Effective\ Rehab\ Rate/100 \times Total\ Network\ Length$
Description	It is the length of pipes that is planned for rehabilitation every year. It should be noted that the length that is actually rehabilitated can be less than the planned length depending upon the length of pipes, in various age groups, which is available for rehabilitation. Moreover, the actual length rehabilitated is constrained by the cash availability for capital works.
Reference for definition of independent variables	
$Effective\ Rehab\ Rate$	Object C4.14
$Total\ Network\ Length$	Object C4.2

C4.16 $\boldsymbol{Desired\ CI\ Rehab\ Length\ 100\ to\ 124}$

Type	Converter
Units	Kilometres
Equation	$Desired\ CI\ Rehab\ Length\ 100\ to\ 124$ $= MIN(Desired\ Rehab\ Length, WaterMains\ Lengths[CI, Age100to124])$
Description	It is the length of CI pipes in age group (100 to 124 years) that is planned for rehabilitation next year. The function $MIN(\ )$ensures that $Desired\ CI\ Rehab\ Length\ 100\ to\ 124$ is equal to the lesser of CI pipe lengths in age group (100 to 124 years) and $Desired\ Rehab\ Length$. Actual length of CI pipes (age group 100 to 124 years) that is rehabilitated can be less than $Desired\ CI\ Rehab\ Length\ 100\ to\ 124$ because of limited cash availability for rehabilitation.

Reference for definition of independent variables	
$Desired\ Rehab\ Length$	Object C4.15
$WaterMains\ Lengths[CI, Age100to124]$	Object C4.1

C4.17 $\boldsymbol{Remaining\ Desired\ Length\ 1}$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 1$ $= Desired\ Rehab\ Length - Desired\ CI\ Rehab\ Length\ 100\ to\ 124$
Description	Among the pipes to be rehabilitated each year, CI pipes in age group (100 to 124 years) have the highest priority. The above equation calculates the remainder of the planned rehabilitation length for other pipe groups.

Reference for definition of independent variables	
$Desired\ Rehab\ Length$	Object C4.15
$Desired\ CI\ Rehab\ Length\ 100\ to\ 124$	Object C4.16

C4.18 $\boldsymbol{Desired\ CI\ Rehab\ Length\ 75\ to\ 99}$

Type	Converter
Units	Kilometres
Equation	$Desired\ CI\ Rehab\ Length\ 75\ to\ 99$ $= MIN(Remaining\ Desired\ Length\ 1, WaterMains\ Lengths[CI, Age75to99])$ $\times Switch\ CI\ Pipes\ 75\ to\ 99\ Rehab$
Description	It is the length of CI pipes in age group (75 to 99 years) that is planned for rehabilitation next year. This length cannot be greater than the current length of CI pipes in age group (75 to 99 years). Moreover, since rehabilitation of CI pipes in age group (100 to 124 years) has a higher priority as compared to that of CI pipes in age group (75 to 99 years), therefore, $Desired\ CI\ Rehab\ Length\ 75\ to\ 99$ cannot be greater than $Remaining\ Desired\ Length\ 1$.

Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 1$	Object C4.17
$WaterMains\ Lengths[CI, Age75to99]$	Object C4.1
$Switch\ CI\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.9

C4.19 $\boldsymbol{Remaining\ Desired\ Length\ 2}$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 2$ $= Remaining\ Desired\ Length\ 1$ $- Desired\ CI\ Rehab\ Length\ 75\ to\ 99$
Description	Among the pipes to be rehabilitated each year, CI pipes in age group (75 to 99 years) have the second highest priority after CI pipes in age group (100 to 124 years). The above equation calculates the remainder of the planned rehabilitation length for pipe groups other than CI pipes (in age groups 75 to 124 years).

Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 1$	Object C4.17
$Desired\ CI\ Rehab\ Length\ 75\ to\ 99$	Object C4.18

C4.20 $\boldsymbol{Desired\ PVC\ Rehab\ Length\ 150\ to\ 174}$

Type	Converter
Units	Kilometres
Equation	$Desired\ PVC\ Rehab\ Length\ 150\ to\ 174$ $= MIN(Remaining\ Desired\ Length\ 2, WaterMains\ Lengths[PVC, Age150to174])$ $\times\ Switch\ PVC\ 150\ to\ 174\ Rehab$
Description	It is the length of PVC pipes in age group (150 to 174 years) that is planned for rehabilitation next year. Length of PVC pipes (age group 150 to 174 years) that is actually rehabilitated can be less than $Desired\ PVC\ Rehab\ Length\ 150\ to\ 174$ because of limited cash availability for rehabilitation.

Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 2$	Object C4.19
$WaterMains\ Lengths[PVC, Age150to174]$	Object C4.1
$Switch\ PVC\ 150\ to\ 174\ Rehab$	Object C1.35

C4.21 $\boldsymbol{Remaining\ Desired\ Length\ 3}$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 3$ $= Remaining\ Desired\ Length\ 2$ $-\ Desired\ PVC\ Rehab\ Length\ 150\ to\ 174$
Description	Among the pipes to be rehabilitated each year, PVC pipes in age group (150 to 174 years) have the third highest priority after CI pipes in age groups (75 to 124 years). The above equation calculates the remainder of the planned rehabilitation length for PVC pipes in age groups (below 150 years).

Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 2$	Object C4.19
$Desired\ PVC\ Rehab\ Length\ 150\ to\ 174$	Object C4.20

C4.22 $\boldsymbol{Desired\ PVC\ Rehab\ Length\ 125\ to\ 149}$

Type	Converter
Units	Kilometres
Equation	$Desired\ PVC\ Rehab\ Length\ 125\ to\ 149$ $= MIN(Remaining\ Desired\ Length\ 3, WaterMains\ Lengths[PVC, Age125to149])$ $\times\ Switch\ PVC\ Pipes\ 125\ to\ 149\ Rehab$
Description	It is the length of PVC pipes in age group (125 to 149 years) that is planned for rehabilitation next year. Length of PVC pipes (age group 125 to 149 years) that is actually rehabilitated can be less than $Desired\ PVC\ Rehab\ Length\ 125\ to\ 149$ because of limited cash availability for rehabilitation.
Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 3$	Object C4.21
$WaterMains\ Lengths[PVC, Age150to174]$	Object C4.1
$Switch\ PVC\ Pipes\ 125\ to\ 149\ Rehab$	Object C1.32

C4.23 $\boldsymbol{Remaining\ Desired\ Length\ 4}$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 4$ $= Remaining\ Desired\ Length\ 3$ $-\ Desired\ PVC\ Rehab\ Length\ 125\ to\ 149$
Description	Among the pipes to be rehabilitated each year, PVC pipes in age group (125 to 149 years) have the fourth highest priority after CI pipes in age groups (75 to 124 years) and PVC pipes in age group (150 to 174 years). The above equation calculates the remainder of the planned rehabilitation length for PVC pipes in age groups (below 125 years).
Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 3$	Object C4.21
$Desired\ PVC\ Rehab\ Length\ 125\ to\ 149$	Object C4.22

C4.24 $\boldsymbol{Desired\ PVC\ Rehab\ Length\ 100\ to\ 124}$

Type	Converter
Units	Kilometres
Equation	$Desired\ PVC\ Rehab\ Length\ 125\ to\ 149$ $= MIN(Remaining\ Desired\ Length\ 4, WaterMains\ Lengths[PVC, Age100to124])$ $\times Switch\ PVC\ Pipes\ 100\ to\ 124\ Rehab$
Description	It is the length of PVC pipes in age group (100 to 124 years) that is planned for rehabilitation next year. Length of PVC pipes (age group 100 to 124 years) that is actually rehabilitated can be less than $Desired\ PVC\ Rehab\ Length\ 100\ to\ 124$ because of limited cash availability for rehabilitation.
Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 4$	Object C4.23
$WaterMains\ Lengths[PVC, Age100to124]$	Object C4.1
$Switch\ PVC\ Pipes\ 100\ to\ 124\ Rehab$	Object C1.28

C4.25 $\boldsymbol{Remaining\ Desired\ Length\ 5}$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 5$ $= Remaining\ Desired\ Length\ 4$ $- Desired\ PVC\ Rehab\ Length\ 100\ to\ 124$
Description	Among the pipes to be rehabilitated each year, PVC pipes in age group (75 to 99 years) have the least priority after CI pipes in age groups (75 to 124 years) and PVC pipes in age groups (100 to 174 years). The above equation calculates the remainder of the planned rehabilitation length for PVC pipes in age group (75 to 99 years).
Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 4$	Object C4.23
$Desired\ PVC\ Rehab\ Length\ 100\ to\ 124$	Object C4.24

C4.26 $\boldsymbol{Desired\ PVC\ Rehab\ Length\ 75\ to\ 99}$

Type	Converter
Units	Kilometres
Equation	$Desired\ PVC\ Rehab\ Length\ 75\ to\ 99$ $= MIN(Remaining\ Desired\ Length\ 5, WaterMains\ Lengths[PVC, Age75to99])$ $\times Switch\ PVC\ Pipes\ 75\ to\ 99\ Rehab$
Description	It is the length of PVC pipes in age group (75 to 99 years) that is planned for rehabilitation next year. Length of PVC pipes (age group 75 to 99 years) that is actually rehabilitated can be less than $Desired\ PVC\ Rehab\ Length\ 75\ to\ 99$ because of limited cash availability for rehabilitation.

Reference for definition of independent variables

$Remaining\ Desired\ Length\ 5$	Object C4.25
$WaterMains\ Lengths[PVC, Age75to99]$	Object C4.1
$Switch\ PVC\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.24

C4.27 $\boldsymbol{Achievable\ Length\ Rehab\ CI}$ **100 to 124**

Type	Converter
Units	Kilometres
Equation	$Achievable\ Length\ Rehab\ CI\ 100\ to\ 124$ $= MIN(Desired\ CI\ Rehab\ Length\ 100\ to\ 124, Cash\ Available\ Cap\ Works$ $/(Inflated\ Unit\ Cost\ Rehab[AG100to124] \times 1000))$
Description	This object calculates the actual length of CI pipes in group (100 to 124 years) that can be rehabilitated given the funds available for capital expenditures. Hence, if sufficient funds ($Cash\ Available\ Cap\ Works$) are not available then $Achievable\ Length\ Rehab\ CI\ 100\ to\ 124$ can be less than the $Desired\ CI\ Rehab\ Length\ 100\ to\ 124$.

Reference for definition of independent variables

$Desired\ CI\ Rehab\ Length\ 100\ to\ 124$	Object C4.16
$Cash\ Available\ Cap\ Works$	Object C5.6
$Inflated\ Unit\ Cost\ Rehabilitation[AG100to124]$	Object C5.35

C4.28 $Remaining\ Desired\ Length\ 10$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 10$ $= Desired\ Rehab\ Length$ $- Achievable\ Length\ Rehab\ CI\ 100\ to\ 124$
Description	Of the total pipe length desired to be rehabilitated in a given year, the pipes that are actually rehabilitated are prioritized according to pipe material and age groups. CI pipes have a higher priority than the PVC pipes for rehabilitation. For a given pipe material, older pipes have a higher priority for rehabilitation. Thus, this model object calculates the remaining pipe length that is still desired to be rehabilitated after CI pipes from age group (100 to 124 years) are rehabilitated.
Reference for definition of independent variables	
$Desired\ Rehab\ Length$	Object C4.15
$Achievable\ Length\ Rehab\ CI\ 100\ to\ 124$	Object C4.27

C4.29 $\boldsymbol{Achievable\ Length\ Rehab\ CI\ 75\ \mathrm{to}\ 99}$

Type	Converter
Units	Kilometres
Equation	$Achievable\ Length\ Rehab\ CI\ 75\ to\ 99$ $= MIN(WaterMains\ Lengths[CI, Age75to99], Remaining\ Desired\ Length\ 10,$ $Cash\ Available\ Rehab\ CI\ 75\ to\ 99/(Inflated\ Unit\ Cost\ Rehab[AG75to99]$ $\times 1000)) \times Switch\ CI\ 75\ to\ 99\ Rehab$
Description	This object calculates the actual length of CI pipes in group (75 to 99 years) that can be rehabilitated given the capital funds available and planned pipe lengths for rehabilitation, remaining after high priority pipes are rehabilitated.

Reference for definition of independent variables	
$WaterMains\ Lengths[CI, Age75to99]$	Object C4.1
$Remaining\ Desired\ Length\ 10$	Object C4.28
$Cash\ Available\ Rehab\ CI\ 75\ to\ 99$	Object C5.8
$Inflated\ Unit\ Cost\ Rehabilitation[AG75to99]$	Object C5.35
$Switch\ CI\ Pipes\ 75\ to\ 99\ Rehab$	Object C1.9

C4.30 $\boldsymbol{Remaining\ Desired\ Length\ 11}$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 11$ $= Remaining\ Desired\ Length\ 10$ $- Achievable\ Length\ Rehab\ CI\ 75\ to\ 99$
Description	CI pipes in age group (75 to 99 year) have second highest priority for rehabilitation among all pipe groups. This object calculates the remainder of pipe lengths desired to be rehabilitated after all CI pipes in age groups (above 75 years) have been rehabilitated.

Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 10$	Object C4.28
$Achievable\ Length\ Rehab\ CI\ 75\ to\ 99$	Object C4.29

C4.31 $Achievable\ Length\ Rehab\ PVC\ 150\ to\ 174$

Type	Converter
Units	Kilometres
Equation	$Achievable\ Length\ Rehab\ PVC\ 150\ to\ 174 = MIN(WaterMains\ Lengths[PVC, Age150to174], Remaining\ Desired\ Length\ 11, Cash\ Available\ Rehab\ PVC\ 150\ to\ 174 /(Inflated\ Unit\ Cost\ Rehab[AG150to174] \times 1000))$
Description	This object calculates the actual length of pipes in group (150 to 174 years) that can be rehabilitated.
Reference for definition of independent variables	
$WaterMains\ Lengths[PVC, Age150to174]$	Object C4.1
$Remaining\ Desired\ Length\ 11$	Object C4.30
$Cash\ Available\ Rehab\ PVC\ 150\ to\ 174$	Object C5.10
$Inflated\ Unit\ Cost\ Rehabilitation[AG150to174]$	Object C5.35

C4.32 $Remaining\ Desired\ Length\ 12$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 12 = Remaining\ Desired\ Length\ 11 - Achievable\ Length\ Rehab\ PVC\ 150\ to\ 174$
Description	CI pipes in age groups (above 75 years) have a higher priority for rehabilitation than the PVC pipes. Among PVC pipes, older pipe groups have a higher priority for rehabilitation. Thus, this object calculates the remainder of pipe lengths desired to be rehabilitated after all CI pipes in age groups (above 75 years) and PVC pipes in age group (150 to 174 years) have been rehabilitated.
Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 11$	Object C4.30
$Achievable\ Length\ Rehab\ PVC\ 150\ to\ 174$	Object C4.31

C4.33 $\boldsymbol{Achievable\ Length\ Rehab\ PVC\ 125\ to\ 149}$

Type	Converter
Units	Kilometres
Equation	$Achievable\ Length\ Rehab\ PVC\ 125\ to\ 149$ $= MIN(WaterMains\ Lengths[PVC, Age125to149],$ $Remaining\ Desired\ Length\ 12, Cash\ Available\ Rehab\ PVC\ 125\ to\ 149$ $/(Inflated\ Unit\ Cost\ Rehab[AG125to149] \times 1000))$
Description	This object calculates the actual length of pipes in group (125 to 149 years) that can be rehabilitated.

Reference for definition of independent variables	
$WaterMains\ Lengths[PVC, Age125to149]$	Object C4.1
$Remaining\ Desired\ Length\ 12$	Object C4.32
$Cash\ Available\ Rehab\ PVC\ 125\ to\ 149$	Object C5.12
$Inflated\ Unit\ Cost\ Rehabilitation[AG125to149]$	Object C5.35

C4.34 $\boldsymbol{Remaining\ Desired\ Length\ 13}$

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 13$ $= Remaining\ Desired\ Length\ 12$ $- Achievable\ Length\ Rehab\ PVC\ 125\ to\ 149$
Description	This object calculates the remainder of pipe lengths desired to be rehabilitated after all CI pipes in age groups (above 75 years) and PVC pipes in age group (above 125 years) have been rehabilitated.

Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 12$	Object C4.32
$Achievable\ Length\ Rehab\ PVC\ 125\ to\ 149$	Object C4.33

C4.35 $\boldsymbol{Achievable\ Length\ Rehab\ PVC}$ 100 to 124

Type	Converter
Units	Kilometres
Equation	$Achievable\ Length\ Rehab\ PVC\ 100\ to\ 124$ $= MIN(WaterMains\ Lengths[PVC, Age100to124],$ $Remaining\ Desired\ Length\ 13, Cash\ Available\ Rehab\ PVC\ 100\ to\ 124$ $/(Inflated\ Unit\ Cost\ Rehab[AG100to124] \times 1000))$
Description	This object calculates the actual length of pipes in group (100 to 124 years) that can be rehabilitated.

Reference for definition of independent variables	
$WaterMains\ Lengths[PVC, Age100to124]$	Object C4.1
$Remaining\ Desired\ Length\ 13$	Object C4.34
$Cash\ Available\ Rehab\ PVC\ 100\ to\ 124$	Object C5.14
$Inflated\ Unit\ Cost\ Rehabilitation[AG100to124]$	Object C5.35

C4.36 $\boldsymbol{Remaining\ Desired\ Length}$ 14

Type	Converter
Units	Kilometres
Equation	$Remaining\ Desired\ Length\ 14$ $= Remaining\ Desired\ Length\ 13$ $- Achievable\ Length\ Rehab\ PVC\ 100\ to\ 124$
Description	This object calculates the remainder of pipe lengths desired to be rehabilitated after all CI pipes in age groups (above 75 years) and PVC pipes in age group (above 100 years) have been rehabilitated.

Reference for definition of independent variables	
$Remaining\ Desired\ Length\ 13$	Object C4.34
$Achievable\ Length\ Rehab\ PVC\ 100\ to\ 124$	Object C4.35

C4.37 $Achievable\ Length\ Rehab\ PVC$ 75 to 99

Type	Converter	
Units	Kilometres	
Equation	$Achievable\ Length\ Rehab\ PVC\ 75\ to\ 99$ $= MIN(WaterMains\ Lengths[PVC, Age75to99],$ $Remaining\ Desired\ Length\ 14, Cash\ Available\ Rehab\ PVC\ 75\ to\ 99$ $/(Inflated\ Unit\ Cost\ Rehab[AG75to99] \times 1000))$	
Description	This object calculates the actual length of pipes in group (75 to 99 years) that can be rehabilitated.	
Reference for definition of independent variables		
$WaterMains\ Lengths[PVC, Age75to99]$		Object C4.1
$Remaining\ Desired\ Length\ 14$		Object C4.36
$Cash\ Available\ Rehab\ PVC\ 75\ to\ 99$		Object C5.16
$Inflated\ Unit\ Cost\ Rehabilitation[AG75to99]$		Object C5.35

C4.38 $Rehab\ Lengths[AG75to99]$

Type	Converter	
Units	Kilometre per year	
Equation	$Rehab\ Lengths[AG75to99]$ $= CI\ Pipes\ 75\ to\ 99\ Rehab + PVC\ Pipes\ 75\ to\ 99\ Rehab$	
Description	Annual length of pipes in age groups (75 to 99 years) that is rehabilitated.	
Reference for definition of independent variables		
$CI\ Pipes\ 75\ to\ 99\ Rehab$		Object C1.10
$PVC\ Pipes\ 75\ to\ 99\ Rehab$		Object C1.25

C4.39 $\boldsymbol{Rehab\ Lengths}[\mathbf{AG100}\boldsymbol{to}\mathbf{124}]$

Type	Converter
Units	Kilometre per year
Equation	$Rehab\ Lengths[AG100to124]$ $= CI\ Pipes\ above\ 100\ Rehab + PVC\ Pipes\ 100\ to\ 124\ Rehab$
Description	Annual length of pipes in age groups (100 to 124 years) that is rehabilitated.
Reference for definition of independent variables	
$CI\ Pipes\ above\ 100\ Rehab$	Object C1.13
$PVC\ Pipes\ 100\ to\ 124\ Rehab$	Object C1.29

C4.40 $\boldsymbol{Rehab\ Lengths}[\mathbf{AG125}\boldsymbol{to}\mathbf{149}]$

Type	Converter
Units	Kilometre per year
Equation	$Rehab\ Lengths[AG125to149] = PVC\ Pipes\ 125\ to\ 149\ Rehab$
Description	Annual length of pipes in age group (125 to 149 years) that is rehabilitated.
Reference for definition of independent variables	
$PVC\ Pipes\ 125\ to\ 149\ Rehab$	Object C1.33

C4.41 $\boldsymbol{Rehab\ Lengths}[\mathbf{AG150}\boldsymbol{to}\mathbf{174}]$

Type	Converter
Units	Kilometre per year
Equation	$Rehab\ Lengths[AG150to174] = PVC\ Pipes\ above\ 150\ Rehab$
Description	Annual length of pipes in age group (150 to 174 years) that is rehabilitated.
Reference for definition of independent variables	
$PVC\ Pipes\ above\ 150\ Rehab$	Object C1.34

C4.42 $\boldsymbol{Total\ Rehab\ Length}$

Type	Converter
Units	Kilometre per year
Equation	$Total\ Rehab\ Length = \sum_{\boldsymbol{CapActivity}} Rehab\ Lengths[\boldsymbol{CapActivity}]$ where $\boldsymbol{CapActivity} = AG75to99, AG100to124, AG125to149, AG150to174$
Description	Annual rehabilitation length for pipes in all age groups $\boldsymbol{CapActivity}$.
Reference for definition of independent variables	
$Rehab\ Lengths[\boldsymbol{CapActivity}]$	Objects C4.38,C4.39,C4.40,C4.41

C4.43 $\boldsymbol{Actual\ Rehab\ Rate}$

Type	Converter
Units	Percent
Equation	$Actual\ Rehab\ Rate = Total\ Rehab\ Length / Total\ Network\ Length \times 100$
Description	It is the fraction of network that is actually rehabilitated in a given year and can be different than the planned or effective rehabilitation rates.
Reference for definition of independent variables	
$Total\ Rehab\ Length$	Object C4.42
$Total\ Network\ Length$	Object C4.2

C4.44 $\boldsymbol{Initial\ Breaks}[\boldsymbol{MainMat}]$

where $\boldsymbol{MainMat} = CI$ and PVC

Type	Converter
Units	Number of breaks per year per kilometre
Equation	Not applicable because it is a constant.
Description	It is the number of initial breaks for each pipe material at the age 0. Its value is specified by the user for both CI and PVC pipes.

C4.45 $\boldsymbol{Deterioration\ Growth\ Rate}[\boldsymbol{MainMat}]$

where $\boldsymbol{MainMat} = CI$ and PVC

Type	Converter
Units	Percent per year
Equation	Not applicable because it is a constant.
Description	It is the annual growth rate in the number of expected breaks for each pipe material. Its value is specified by the user for both CI and PVC pipes.

C4.46 $\boldsymbol{Breaks}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC;

and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$

Type	Converter
Units	Breaks per year
Equation	$Breaks[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $= Initial\ Breaks[\boldsymbol{MainMat}]$ $\times e^{Deterioration\ Growth\ Rate[\boldsymbol{MainMat}]/100 \times Average\ Age\ for\ Age\ Groups[\boldsymbol{AgeGroups}]}$ $\times WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ for $\boldsymbol{MainMat} = CI$ and PVC; and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149$, and $150\ to\ 174$
Description	This object calculates expected number of annual breaks for each pipe group (by material and age).

Reference for definition of independent variables	
$Initial\ Breaks[\boldsymbol{MainMat}]$	Object C4.44
$Deterioration\ Growth\ Rate[\boldsymbol{MainMat}]$	Object C4.45
$Average\ Age\ for\ Age\ Groups[\boldsymbol{AgeGroups}]$	Object C4.3
$WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.1

C4.47 $\boldsymbol{Total\ Breaks}$

Type	Converter
Units	Number of breaks per year
Equation	$Total\ Breaks = \sum_{\boldsymbol{MainMat}} \sum_{\boldsymbol{AgeGroups}} Breaks[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ where $\boldsymbol{MainMat} = CI, PVC$; and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149, 150\ to\ 174$
Description	Annual number of breaks for the whole network

Reference for definition of independent variables	
$Breaks[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.46

C4.48 $\boldsymbol{Leakage\ Fractions}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC;

and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$

Type	Converter
Units	Percent
Equation	Not applicable because it is a constant.
Description	For any pipe group of a given material and age group, $Leakage\ Fraction[\boldsymbol{MainMat}, \boldsymbol{AgeGroup}]$ represents the fraction of annual water consumption that would be lost as leakage if the whole network were comprised of pipes belonging to the same material and age group. These values are specified by the user for all pipe groups.

C4.49 $\textit{Leakage Volumes}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC;

and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$

Type	Converter
Units	Cubic metres per year.
Equation	$\textit{Leakage Volumes}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}] = \textit{Pipe Fractions by Material\&Age}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}] /100 \times \textit{Leakage Fractions}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]/100 \times \textit{Annual Water Consumption}$ where $\boldsymbol{MainMat} = CI, PVC$; and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149, 150\ to\ 174$
Description	It is the volume of water lost as leakage from pipes in each group (by material and age).

Reference for definition of independent variables	
$\textit{Pipe Fractions by Material\&Age}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.6
$\textit{Leakage Fractions}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.48
$\textit{Annual Water Consumption}$	Object C2.25

C4.50 $\textit{Annual Leakage}$

Type	Flow
Units	Cubic metres per year.
Equation	$\textit{Annual Leakage} = \sum_{\boldsymbol{MainMat}} \sum_{\boldsymbol{AgeGroups}} \textit{Leakage Volumes}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ for $\boldsymbol{MainMat} = CI, PVC$; and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149, 150\ to\ 174$
Description	It is the annual volume of water lost as leakage from the whole network.

Reference for definition of independent variables	
$\textit{Leakage Volumes}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.49

C4.51 $\boldsymbol{Leaked\ Water\ Volume}$

Type	Stock
Units	Cubic metres
Equation	$Leaked\ Water\ Volume(t)$ $= Leaked\ Water\ Volume(t - dt) + (Annual\ Leakage) \times DT$
Description	It is the cumulative volume of water lost as leakage since the start of the simulation.

Reference for definition of independent variables

$Annual\ Leakage$	Object C4.50

C4.52 $\boldsymbol{Annual\ Water\ Volume\ Purchased}$

Type	Converter
Units	Cubic metres per year.
Equation	$Annual\ Water\ Volume\ Purchased$ $= Annual\ Water\ Consumption + Annual\ Leakage$
Description	It is the total annual volume of treated water that the utility purchases. It is the sum of water actually consumed by (and billed to) the consumers and the volume of water that is lost as leakage without generating any revenue.

Reference for definition of independent variables

$Annual\ Water\ Consumption$	Object C2.25
$Annual\ Leakage$	Object C4.50

C4.53 $\boldsymbol{Annual\ Leakage\ Fraction}$

Type	Converter
Units	Percent
Equation	$Annual\ Leakage\ Fraction$ $= Annual\ Leakage/Annual\ Water\ Consumption \times 100$
Description	It is the leaked water as a fraction of the annual water consumption.

Reference for definition of independent variables

$Annual\ Leakage$	Object C4.50
$Annual\ Water\ Consumption$	Object C2.25

C5 Finance Auxiliary Sector

C5.1 *Average Revenue*

Type	In the model this variable is calculated using a combination of stocks-flows-converters objects which is not provided here but the essential idea is represented by the following equation.
Units	Dollars per year
Equation	$Average\ Revenue_t = \left(\sum_{k=t-Averaging\ Period}^{t-1} Revenue_k \right) / Averaging\ Period$ where t is the current time of simulation.
Description	It is the average of revenues over the most recent $Averaging\ Period$.
Reference for definition of independent variables	
$Revenue$	Object C3.16
$Averaging\ Period$	Object C5.2

C5.2 *Averaging Period*

Type	Converter (constant)
Units	Years
Equation	Not applicable because it is a constant.
Description	It is the time period over which revenue is averaged.

C5.3 *Last Year Fee*

Type	Converter
Units	Dollars per cubic metre
Equation	$LastYear\ Fee_t = Water\ Fee_{t-1}$ where t is the current time of simulation.
Description	It is the value of $Water\ Fee$, one year before the current time t
Reference for definition of independent variables	
$Water\ Fee$	Object C3.1

C5.4 $Annual\ Unused\ Debt\ Capacity$

Type	Converter
Units	Dollars per year
Equation	$Annual\ Unused\ Debt\ Capacity = Maximum\ Debt\ Capacity/100 \times Average\ Revenue - Current\ Debt\ Service$
Description	It is the difference between the maximum allowable debt service charges for the utility and its current actual debt service charges.

Reference for definition of independent variables	
$Maximum\ Debt\ Capacity$	Object C5.5
$Average\ Revenue$	Object C5.1
$Current\ Debt\ Service$	Object C5.42

C5.5 $Maximum\ Debt\ Capacity$

Type	Converter (constant)
Units	Percent
Equation	Not applicable because it is a constant.
Description	A utility may be constrained so as not to issue debt for which $Debt\ Service$ will amount to be more than a certain fraction of its revenue. $Maximum\ Debt\ Capacity$ represents that upper limit for $Debt\ Service$ as a percentage of revenue.

C5.6 $\boldsymbol{Cash\ Available\ Cap\ Works}$

Type	Converter
Units	Dollars
Equation	$Cash\ Available\ Cap\ Works = MAX\big(0, (Working\ Capital/DT - (OpEx + Principal\ Payment) \times DT)\big)$
Description	Amount of cash available to the utility in a given year to carry out capital works projects. The above equation shows that operational expenditures and repayment of loans have a higher priority than the capital works expenses. Hence, cash available to be spent on capital works projects is only what is left from utility's total cash after accounting for OpEx and principal payment obligations.

Reference for definition of independent variables	
$Working\ Capital$	Object C3.4
$OpEx$	Object C3.18
$Principal\ Payment$	Object C3.11

C5.7 $\boldsymbol{Cash\ Used\ Rehab\ CI\ 100\ to\ 124}$

Type	Converter
Units	Dollars
Equation	$Cash\ Used\ Rehab\ CI\ 100\ to\ 124 = Achievable\ Length\ Rehab\ CI\ 100\ to\ 124 \times 1000 \times Inflated\ Unit\ Cost\ Rehab[AG100to124]$
Description	This object calculates the amount of cash that is used on rehabilitating CI pipes in age group (100 to 124 years).

Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ CI\ 100\ to\ 124$	Object C4.27
$Inflated\ Unit\ Cost\ Rehab[AG100to124]$	Object C5.35

C5.8 $\boldsymbol{Cash\ Available\ Rehab\ CI\ 75\ to\ 99}$

Type	Converter
Units	Dollars
Equation	$Cash\ Available\ Rehab\ CI\ 75\ to\ 99 = Cash\ Available\ Cap\ Works - Cash\ Used\ Rehab\ CI\ 100\ to\ 124$
Description	Amount of cash available for rehabilitation of CI pipes in age group (75 to 99 years).
Reference for definition of independent variables	
$Cash\ Available\ Cap\ Works$	Object C5.6
$Cash\ Used\ Rehab\ CI\ 100\ to\ 124$	Object C5.7

C5.9 $\boldsymbol{Cash\ Used\ Rehab\ CI\ 75\ to\ 99}$

Type	Converter
Units	Dollars
Equation	$Cash\ Used\ Rehab\ CI\ 75\ to\ 99 = Achievable\ Length\ Rehab\ CI\ 75\ to\ 99 \times 1000 \times Inflated\ Unit\ Cost\ Rehab[AG75to99]$
Description	Calculates the amount of cash that is used on rehabilitating CI pipes in age group (75 to 99 years).
Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ CI\ 75\ to\ 99$	Object C4.29
$Inflated\ Unit\ Cost\ Rehab[AG75to99]$	Object C5.35

C5.10 $\boldsymbol{Cash\ Available\ Rehab\ PVC\ 150\ to\ 174}$

Type	Converter
Units	Dollars
Equation	$Cash\ Available\ Rehab\ PVC\ 150\ to\ 174$ $= Cash\ Available\ Rehab\ CI\ 75\ to\ 99$ $- Cash\ Used\ Rehab\ CI\ 75\ to\ 99$
Description	Amount of cash available for rehabilitation of PVC pipes in age group (150 to 174 years).
Reference for definition of independent variables	
$Cash\ Available\ Rehab\ CI\ 75\ to\ 99$	Object C5.8
$Cash\ Used\ Rehab\ CI\ 75\ to\ 99$	Object C5.9

C5.11 $\boldsymbol{Cash\ Used\ Rehab\ PVC\ 150\ to\ 174}$

Type	Converter
Units	Dollars
Equation	$Cash\ Used\ Rehab\ PVC\ 150\ to\ 174$ $= Achievable\ Length\ Rehab\ PVC\ 150\ to\ 174 \times 1000$ $\times Inflated\ Unit\ Cost\ Rehab[AG150to174]$
Description	This object calculates the amount of cash that is used on rehabilitating PVC pipes in age group (150 to 174 years).
Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ PVC\ 150\ to\ 174$	Object C4.31
$Inflated\ Unit\ Cost\ Rehab[AG150to174]$	Object C5.35

C5.12 $\boldsymbol{Cash\ Available\ Rehab\ PVC\ 125\ to\ 149}$

Type	Converter
Units	Dollars
Equation	$Cash\ Available\ Rehab\ PVC\ 125\ to\ 149$ $= Cash\ Available\ Rehab\ PVC\ 150\ to\ 174$ $- Cash\ Used\ Rehab\ PVC\ 150\ to\ 174$
Description	Amount of cash available for rehabilitation of PVC pipes in age group (125 to 149 years).
Reference for definition of independent variables	
$Cash\ Available\ Rehab\ PVC\ 150\ to\ 174$	Object C5.10
$Cash\ Used\ Rehab\ PVC\ 150\ to\ 174$	Object C5.11

C5.13 $\boldsymbol{Cash\ Used\ Rehab\ PVC\ 125\ to\ 149}$

Type	Converter
Units	Dollars
Equation	$Cash\ Used\ Rehab\ PVC\ 125\ to\ 149$ $= Achievable\ Length\ Rehab\ PVC\ 125\ to\ 149 \times 1000$ $\times Inflated\ Unit\ Cost\ Rehab[AG125to149]$
Description	This object calculates the amount of cash that is used on rehabilitating PVC pipes in age group (125 to 149 years).
Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ PVC\ 125\ to\ 149$	Object C4.33
$Inflated\ Unit\ Cost\ Rehab[AG125to149]$	Object C5.35

C5.14 $Cash\ Available\ Rehab\ PVC\ 100\ to\ 124$

Type	Converter
Units	Dollars
Equation	$Cash\ Available\ Rehab\ PVC\ 100\ to\ 124 = Cash\ Available\ Rehab\ PVC\ 125\ to\ 149 - Cash\ Used\ Rehab\ PVC\ 125\ to\ 149$
Description	Amount of cash available for rehabilitation of PVC pipes in age group (100 to 125 years).
Reference for definition of independent variables	
$Cash\ Available\ Rehab\ PVC\ 125\ to\ 149$	Object C5.12
$Cash\ Used\ Rehab\ PVC\ 125\ to\ 149$	Object C5.13

C5.15 $Cash\ Used\ Rehab\ PVC\ 100\ to\ 124$

Type	Converter
Units	Dollars
Equation	$Cash\ Used\ Rehab\ PVC\ 100\ to\ 124 = Achievable\ Length\ Rehab\ PVC\ 100\ to\ 124 \times 1000 \times Inflated\ Unit\ Cost\ Rehab[AG100to124]$
Description	This object calculates the amount of cash that is used on rehabilitating PVC pipes in age group (100 to 124 years).
Reference for definition of independent variables	
$Achievable\ Length\ Rehab\ PVC\ 100\ to\ 124$	Object C4.35
$Inflated\ Unit\ Cost\ Rehab[AG100to124]$	Object C5.35

C5.16 $\boldsymbol{Cash\ Available\ Rehab\ PVC\ 75\ to\ 99}$

Type	Converter
Units	Dollars
Equation	$Cash\ Available\ Rehab\ PVC\ 75\ to\ 99 = Cash\ Available\ Rehab\ PVC\ 100\ to\ 124 - Cash\ Used\ Rehab\ PVC\ 100\ to\ 124$
Description	Amount of cash available for rehabilitation of PVC pipes in age group (100 to 125 years).
Reference for definition of independent variables	
$Cash\ Available\ Rehab\ PVC\ 100\ to\ 124$	Object C5.14
$Cash\ Used\ Rehab\ PVC\ 100\ to\ 124$	Object C5.15

C5.17 $\boldsymbol{Cash\ Required\ by\ Cap\ Activity[AG75to99]}$

Type	Converter
Units	Dollars
Equation	$Cash\ Required\ by\ Cap\ Activity[AG75to99] = (Desired\ CI\ Rehab\ Length\ 75\ to\ 99 + Desired\ PVC\ Rehab\ Length\ 75\ to\ 99) \times 1000 \times Inflated\ Unit\ Cost\ Rehab[AG75to99]$
Description	Calculates the cash required to be able to achieve the rehabilitation of desired length of pipes in age group (75 to 99 years) during next year.
Reference for definition of independent variables	
$Desired\ CI\ Rehab\ Length\ 75\ to\ 99$	Object C4.18
$Desired\ PVC\ Rehab\ Length\ 75\ to\ 99$	Object C4.26
$Inflated\ Unit\ Cost\ Rehab[AG75to99]$	Object C5.35

C5.18 $\boldsymbol{Cash\ Required\ by\ Cap\ Activity[AG100to124]}$

Type	Converter
Units	Dollars
Equation	$Cash\ Required\ by\ Cap\ Activity[AG100to124]$ $= (Desired\ CI\ Rehab\ Length\ 100\ to\ 124$ $+ Desired\ PVC\ Rehab\ Length\ 100\ to\ 124) \times 1000$ $\times Inflated\ Unit\ Cost\ Rehab[AG100to124]$
Description	Calculates the cash required to be able to achieve rehabilitation of the desired length of pipes in age group (100 to 124 years) during next year.
Reference for definition of independent variables	
$Desired\ CI\ Rehab\ Length\ 100\ to\ 124$	Object C4.16
$Desired\ PVC\ Rehab\ Length\ 100\ to\ 124$	Object C4.24
$Inflated\ Unit\ Cost\ Rehab[AG100to124]$	Object C5.35

C5.19 $\boldsymbol{Cash\ Required\ by\ Cap\ Activity[AG125to149]}$

Type	Converter
Units	Dollars
Equation	$Cash\ Required\ by\ Cap\ Activity[AG125to149]$ $= (Desired\ PVC\ Rehab\ Length\ 125\ to\ 149) \times 1000$ $\times Inflated\ Unit\ Cost\ Rehab[AG125to149]$
Description	Calculates the cash required to be able to achieve rehabilitation of the desired length of pipes in age group (125 to 149 years) during next year.
Reference for definition of independent variables	
$Desired\ PVC\ Rehab\ Length\ 125\ to\ 149$	Object C4.22
$Inflated\ Unit\ Cost\ Rehab[AG125to149]$	Object C5.35

C5.20 $\boldsymbol{Cash\ Required\ by\ Cap\ Activity}[\boldsymbol{AG150to174}]$

Type	Converter
Units	Dollars
Equation	$Cash\ Required\ by\ Cap\ Activity[AG150to174]$ $= (Desired\ PVC\ Rehab\ Length\ 150\ to\ 174) \times 1000$ $\times Inflated\ Unit\ Cost\ Rehab[AG150to174]$
Description	Calculates the cash required to be able to achieve rehabilitation of the desired length of pipes in age group (150 to 174 years) during next year.
Reference for definition of independent variables	
$Desired\ PVC\ Rehab\ Length\ 150\ to\ 174$	Object C4.20
$Inflated\ Unit\ Cost\ Rehab[AG150to174]$	Object C5.35

C5.21 $\boldsymbol{Cash\ Required\ Capital\ Works}$

Type	Converter
Units	Dollars
Equation	$Cash\ Required\ Capital\ Works$ $= Cash\ Required\ by\ Cap\ Activity[AG74to99]$ $+ Cash\ Required\ by\ Cap\ Activity[AG100to124]$ $+ Cash\ Required\ by\ Cap\ Activity[AG125to149]$ $+ Cash\ Required\ by\ Cap\ Activity[AG150to174]$
Description	Calculates the total cash required for rehabilitation of pipes during next year.
Reference for definition of independent variables	
$Cash\ Required\ by\ Cap\ Activity[AG74to99]$	Object C5.17
$Cash\ Required\ by\ Cap\ Activity[AG100to124]$	Object C5.18
$Cash\ Required\ by\ Cap\ Activity[AG125to149]$	Object C5.19
$Cash\ Required\ by\ Cap\ Activity[AG150to174]$	Object C5.20

C5.22 $\boldsymbol{Unit\ Cost\ Maintenance}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC;

and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$

Type	Converter
Units	Dollars per metre per year
Equation	Not applicable since it is a constant.
Description	It represents the annual cost incurred on maintaining one metre of pipe of given material and age group. The cost drivers that this variable captures include (salaries, administrative and government overheads), maintenance activities (flushing and minor repairs) and emergency expenditures (watermain breaks) and pumping costs for the network. Values for each pipe material and age groups are specified by the user.

C5.23 $\boldsymbol{MaintCost\ Inflation}$

Type	Converter
Units	Percent per year
Equation	Not applicable since it is a constant.
Description	It is the annual inflation rate for maintenance costs.

C5.24 $\boldsymbol{Inflated\ Unit\ Cost\ Maintenance}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC;

and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$

Type	Converter
Units	Dollars per metre per year
Equation	$Inflated\ Unit\ Cost\ Maintenance[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $= Unit\ Cost\ Maintenance[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $\times e^{MaintCost\ Inflation/100 \times TIME}$ where $\boldsymbol{M} = CI, PVC$; and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$
Description	$MaintCost\ Inflation$ is used to inflate the $Unit\ Cost\ Maintenance$ to the prevailing time $TIME$ of the simulation.
Reference for definition of independent variables	
$Unit\ Cost\ Maintenance[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C5.22
$MaintCost\ Inflation$	Objet C5.23

C5.25 $\boldsymbol{Maintenance\ Ex\ by\ Material\&Age}[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$

where $\boldsymbol{MainMat} = CI$ and PVC;

and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$

Type	Converter
Units	Dollars per year
Equation	$Maintenance\ Ex[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $= Inflated\ Unit\ Cost\ Maintenance[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ $\times WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}] \times 1000$ where $\boldsymbol{MainMat} = CI, PVC$; and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$
Description	Maintenance cost incurred on pipes of each material in each age group.

Reference for definition of independent variables	
$Inflated\ Unit\ Cost\ Maintenance[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C5.24
$WaterMains\ Lengths[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C4.1

C5.26 $\boldsymbol{Maintenance\ Ex}$

Type	Converter
Units	Dollars per year
Equation	$Maintenance\ Ex = \sum_{\boldsymbol{MainMat}} \sum_{\boldsymbol{AgeGroups}} Maintenance\ Ex[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$ where $\boldsymbol{M} = CI, PVC$; and $\boldsymbol{AgeGroups} = 0to24, 25to49, 50to74, 75to99, 100to124, 125to149,$ and $150\ to\ 174$
Description	Annual maintenance costs incurred for the whole network.

Reference for definition of independent variables	
$Maintenance\ Ex[\boldsymbol{MainMat}, \boldsymbol{AgeGroups}]$	Object C5.25

C5.27 $Unit\ Price\ Water\ Treatment$

Type	Converter (constant)
Units	Dollars per cubic metre
Equation	Not applicable since it a constant.
Description	It is the price that the utility pays for each cubic metre of water that is pumped into the network. Its value is specified by the user.

C5.28 $Construction\ Inflation$

Type	Converter
Units	Percent per year
Equation	Not applicable since it is a constant.
Description	It is the annual inflation rate for capital costs and water treatment costs.

C5.29 $Inflated\ Unit\ Price\ WT$

Type	Converter
Units	Dollars per metre per year
Equation	$Inflated\ Unit\ Price\ WT = Unit\ Price\ Water\ Treatment \times e^{Construction\ Inflation/100 \times TIME}$
Description	$Construction\ Inflation$ is used to inflate the $Unit\ Price\ Water\ Treatment$ to the prevailing time $TIME$ of the simulation.
Reference for definition of independent variables	
$Unit\ Price\ Water\ Treatment$	Object C5.27
$Construction\ Inflation$	Object C5.28

C5.30 $Water\ Purchase\ Ex$

Type	Converter
Units	Dollars per year
Equation	$Water\ Purchase\ Ex = Annual\ Water\ Volume\ Purchased \times Inflated\ Unit\ Price\ WT$
Description	Annual expenses incurred by the utility on purchasing the total annual supplies of treated water.
Reference for definition of independent variables	
$Annual\ Water\ Volume\ Purchased$	Object C4.52
$Inflated\ Unit\ Price\ WT$	Object C5.29

C5.31 $Borrowing\ Rate$

Type	Converter
Units	Percent per year
Equation	Not applicable since it is a constant.
Description	It is the annual interest rate on borrowing. Its value is specified by the user.

C5.32 $Savings\ Rate$

Type	Converter
Units	Percent per year
Equation	Not applicable since it is a constant.
Description	It is the annual interest that the utility earns on its cash reserves. Its value is specified by the user.

C5.33 $\boldsymbol{CPI}$

Type	Converter
Units	Percent per year
Equation	Not applicable since it is a constant.
Description	CPI represents the consumer price index that is the general inflation in the economy. Its value is specified by the user.

C5.34 $\boldsymbol{Unit\ Cost\ Rehabilitation}[\boldsymbol{CapActivity}]$

where $\boldsymbol{CapActivity} = AG75to99, AG100to124, AG125to149, AG150to174$

Type	Converter
Units	Dollars per metre
Equation	Not applicable since it a constant.
Description	It is the cost of rehabilitating one metre of a pipe in a given age group. Its value is specified by the user.

C5.35 $\boldsymbol{Inflated\ Unit\ Cost\ Rehab}[\boldsymbol{CapActivity}]$

where $\boldsymbol{CapActivity} = AG75to99, AG100to124, AG125to149, AG150to174$

Type	Converter
Units	Dollars per metre
Equation	$Inflated\ Unit\ Cost\ Rehab[\boldsymbol{CapActivity}] = Unit\ Cost\ Rehabilitation[\boldsymbol{CapActivity}] \times e^{Construction\ Inflation/100 \times TIME}$ where $\boldsymbol{CapActivity} = AG75to99, AG100to124, AG125to149, AG150to174$
Description	$Construction\ Inflation$ is used to inflate the $Unit\ Cost\ Rehabilitation$ to the prevailing time $TIME$ of the simulation.
Reference for definition of independent variables	
$Unit\ Cost\ Rehabilitation[\boldsymbol{CapActivity}]$	Object C5.34
$Construction\ Inflation$	Object C5.28

C5.36 $\boldsymbol{CapEx\ byAcitivity}[\boldsymbol{CapActivity}]$

where $\boldsymbol{CapActivity} = AG75to99, AG100to124, AG125to149, AG150to174$

Type	Converter
Units	Dollars per metre
Equation	$CapEx\ byActivity[\boldsymbol{CapActivity}]$ $= Rehab\ Lengths[\boldsymbol{CapActivity}]$ $\times Inflated\ Unit\ Cost\ Rehab[\boldsymbol{CapActivity}] \times 1000$ where $\boldsymbol{CapActivity} = AG75to99, AG100to124, AG125to149, AG150to174$
Description	Annual capital expenditures incurred on rehabilitation of pipes of various age groups.
Reference for definition of independent variables	
$Rehab\ Lengths[\boldsymbol{CapActivity}]$	Objects C4.38,C4.39,C4.40,C4.41
$Inflated\ Unit\ Cost\ Rehab[\boldsymbol{CapActivity}]$	Object C5.35

C5.37 $\boldsymbol{Cash\ Required\ Interest\ Payment}$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ Interest\ Payment = Interest\ Ex$
Description	Cash requirement for paying off interest on outstanding debt.
Reference for definition of independent variables	
$InterestEx$	Object C3.22

C5.38 $\boldsymbol{Cash\ Required\ MaintenanceEx}$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ MaintenanceEx = Maintenance\ Ex \times e^{MaintCost\ Inflation/100 \times DT}$
Description	Cash requirement for maintenance expenditures.
Reference for definition of independent variables	
$Maintenance\ Ex$	Object C5.26
$MaintCost\ Inflation$	Object C5.23

C5.39 $\boldsymbol{Cash\ Required\ Principal\ Payment}$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ Principal\ Payment = Annual\ Serials$
Description	Required amount of cash for paying off principal portion of debt.
Reference for definition of independent variables	
$Annual\ Serials$	Object C3.12

C5.40 $\boldsymbol{Cash\ Required\ Water\ Purchase}$

Type	Converter
Units	Dollars per year
Equation	$Cash\ Required\ Water\ Purchase = Water\ Purchase\ Ex \times e^{Construction\ Inflation/100 \times DT}$
Description	It is the cash required per year for purchasing treated water.
Reference for definition of independent variables	
$Water\ Purchase\ Ex$	Object C5.30
$Construction\ Inflation$	Object C5.28

C5.41 *Cash Required Debt Service*

Type	Converter
Units	Dollars per year
Equation	$\mathit{Cash\ Required\ Debt\ Service} = \mathit{Annual\ Serials} + (\mathit{Serial\ Launch} - \mathit{Serial\ Retirement}) \times \mathit{DT} + \{\mathit{Debt} + (\mathit{Debt\ Issue} - \mathit{Principal\ Payment}) \times \mathit{DT}\} \times \mathit{Borrowing\ Rate}/100$
Description	Annual cash requirement for total debt service that is payment obligation of principal portion and interest accrued during a given year.

Reference for definition of independent variables	
$\mathit{Annual\ Serials}$	Object C3.12
$\mathit{Serial\ Launch}$	Object C3.13
$\mathit{Serial\ Retirement}$	Object C3.14
Debt	Object C3.9
$\mathit{Debt\ Issue}$	Object C3.10
$\mathit{Principal\ Payment}$	Object C3.11
$\mathit{Borrowing\ Rate}$	Object C5.31

C5.42 *Current Debt Service*

Type	Converter
Units	Dollars per year
Equation	$\mathit{Current\ Debt\ Service} = \mathit{Principal\ Payment} + \mathit{InterestEx}$
Description	Current year’s cash requirement for debt service that is payment obligation of principal portion and interest expense.

Reference for definition of independent variables	
$\mathit{Principal\ Payment}$	Object C3.11
$\mathit{InterestEx}$	Object C3.22

C5.43 $Debt\ Service\ Ratio$

Type	Converter
Units	Dollars per year
Equation	$Debt\ Service\ Ratio = Current\ Debt\ Service/Average\ Revenue \times 100$
Description	Current year's cash requirement for debt service that is payment obligation of principal portion and interest expense.
Reference for definition of independent variables	
$Current\ Debt\ Service$	Object C5.42
$Average\ Revenue$	Object C5.1

C5.44 $Current\ Cash\ Required$

Type	Converter
Units	Dollars per year
Equation	$Current\ Cash\ Required = Cash\ Required\ Capital\ Works + Cash\ Required\ Interest\ Payment + Cash\ Required\ MaintenanceEx + Cash\ Required\ Principal\ Payment + Cash\ Required\ Water\ Purchase$
Description	It is the total cash required for the current year for various expenditure categories.
Reference for definition of independent variables	
$Cash\ Required\ Capital\ Works$	Object C5.21
$Cash\ Required\ Interest\ Payment$	Object C5.37
$Cash\ Required\ MaintenanceEx$	Object C5.38
$Cash\ Required\ Principal\ Payment$	Object C5.39
$Cash\ Required\ Water\ Purchase$	Object C5.40

C5.45 $Desired\ Reserve\ Fraction$

Type	Converter
Units	Percent of network length
Equation	Not applicable because it is a constant.
Description	It is the fraction of the network length whose replacement cost is the targeted level for the utility to build its reserves.

C5.46 $Desired\ Fund\ Reserve$

Type	Converter
Units	Dollars
Equation	$Desired\ Fund\ Reserve = Desired\ Reserve\ Fraction/100 \times Total\ Network\ Length \times 1000 \times Inflated\ Unit\ Cost\ Rehab[AG100to124]$
Description	Calculates the desired cash reserve level of the utility as the replacement cost of $Desired\ Reserve\ Fraction(\%)$ of the total network.
Reference for definition of independent variables	
$Desired\ Reserve\ Fraction$	Object C5.45
$Total\ Network\ Length$	Object C4.2
$Inflated\ Unit\ Cost\ Rehab[AG100to124]$	Object C5.35

C5.47 $Projected\ Expenditures$

Type	Converter
Units	Dollars per year.
Equation	$Projected\ Expenditures = Cash\ Required\ MaintenanceEx + Cash\ Required\ Water\ Purchase + Cash\ Required\ Debt\ Service + Cash\ Required\ Capital\ Works$
Description	It is the sum of cash requirements for various expenditure categories of the utility for the next year.
Reference for definition of independent variables	
$Cash\ Required\ MaintenanceEx$	Object C5.38
$Cash\ Required\ WaterPurchase$	Object C5.40
$Cash\ Required\ Debt\ Service$	Object C5.41
$Cash\ Required\ Capital\ Works$	Object C5.21

C5.48 $Reserve\ Contribution$

Type	Converter
Units	Dollars per year.
Equation	$Reserve\ Contribution = IF(Cash\ Available\ Cap\ Works < Cash\ Required\ Capital\ Works)\ THEN\ 0\ ELSE\ (Desired\ Fund\ Reserve - Fund\ Balance)$
Description	It represents the amount by which the utility is short of reaching its targeted/desired reserve levels. However, if the utility cannot generate the cash that it needs for its current required capital works projects then no contribution is made to the reserves.
Reference for definition of independent variables	
$Cash\ Available\ Cap\ Works$	Object C5.6
$Cash\ Required\ Capital\ Works$	Object C5.21
$Desired\ Fund\ Reserve$	Object C5.46
$Fund\ Balance$	Object C3.15

C5.49 $\mathit{Next\ Year\ Cash\ Required}$

Type	Converter
Units	Dollars per year.
Equation	$\mathit{Next\ Year\ Cash\ Required} = \mathit{Projected\ Expenditures} + \mathit{Reserve\ Contribution}$
Description	It is the total cash requirements of the utility for next year and includes cash requirements for expenditure categories as well as cash to build up reserves.
Reference for definition of independent variables	
$\mathit{Projected\ Expenditures}$	Object C5.47
$\mathit{Reserve\ Contribution}$	Object C5.48

C5.50 $\mathit{Required\ Fee}$

Type	Converter
Units	Dollars per cubic metre
Equation	$\mathit{Required\ Fee} = \mathit{Next\ Year\ Cash\ Required} / \mathit{Annual\ Water\ Consumption}$
Description	It is the water fee that generates sufficient revenue to pay for all the next year's requirements. It is the water fee value that the utility would prefer to implement.
Reference for definition of independent variables	
$\mathit{Next\ Year\ Cash\ Required}$	Object C5.49
$\mathit{Annual\ Water\ Consumption}$	Object C2.25

C5.51 $\mathit{Proposed\ Fee\ Change}$

Type	Converter
Units	Dollars per cubic metre
Equation	$\mathit{Proposed\ Fee\ Change} = \mathit{Required\ Fee} - \mathit{Water\ Fee}$
Description	It is the change in $\mathit{Water\ Fee}$ required to bring it to the utility's preferred level of $\mathit{Required\ Fee}$. It should be noted that this proposed change in fee does not necessarily have to be always a positive value.
Reference for definition of independent variables	
$\mathit{Required\ Fee}$	Object C5.50
$\mathit{Water\ Fee}$	Object C3.1

C5.52 *Minimum Cash Required*

Type	Converter
Units	Dollars per year.
Equation	$Minimum\ Cash\ Required = IF\ (Fund\ Balance < 0)\ AND\ (Reserve\ Contribution = 0)\ THEN\ (Cash\ Required\ Water\ Purchase + Cash\ Required\ MaintenanceEx + Cash\ Required\ Debt\ Service - Fund\ Balance)\ ELSE\ (Cash\ Required\ Water\ Purchase + Cash\ Required\ MaintenanceEx + Cash\ Required\ Debt\ Service)$
Description	Municipal governments are not allowed to borrow for financing their operational expenditures or servicing debt, these costs need to be paid for through revenues. Hence, the water fee at any time should be enough to raise revenue at least for these cost categories. The above equation calculates this minimum required cash for next year.
Reference for definition of independent variables	
$Cash\ Required\ MaintenanceEx$	Object C5.38
$Cash\ Required\ WaterPurchase$	Object C5.40
$Cash\ Required\ Debt\ Service$	Object C5.41
$Fund\ Balance$	Object C3.15
$Reserve\ Contribution$	Object C5.48

C5.53 $\boldsymbol{Minimum\ Required\ Fee}$

Type	Converter	
Units	Dollars per cubic metre	
Equation	$Mini\ mum\ Required\ Fee = Minimum\ Cash\ Required/Annual\ Water\ Consumption$	
Description	It is the fee that generates revenue sufficient to pay for the expenditures that cannot be financed through borrowing.	
Reference for definition of independent variables		
$Minimum\ Cash\ Required$	Object C5.52	
$Annual\ Water\ Consumption$	Object C2.25	

C5.54 $\boldsymbol{Current\ Year\ Fee\ Ceiling}$

Type	Converter	
Units	Dollars per cubic metre	
Equation	$Current\ Year\ Fee\ Ceiling = (1 + Maximum\ Fee\ Hike\ Rate/100) \times Last\ Year\ Fee$	
Description	It is the maximum value that water fee can attain during the current year.	
Reference for definition of independent variables		
$Maximum\ Fee\ Hike\ Rate$	Object C2.22	
$Last\ Year\ Fee$	Object C5.3	

C5.55 $\boldsymbol{Accepted\ Fee\ Change}$

Type	Converter
Units	Dollars per cubic metre
Equation	$Accepted\ Fee\ Change = MIN\big(Proposed\ Fee\ Change, (Proposed\ Fee\ Change \times Consumers\ Fee\ Hike\ Acceptability/100)\big)$
Description	It is the fee change (increase) acceptable to consumers.

C5.56 $\boldsymbol{New\ Water\ Fee}$

Type	Converter
Units	Dollars per cubic metre
Equation	$New\ Water\ Fee$ $= IF\ (Required\ Fee$ $< Water\ Fee)\ THEN\ (Required\ Fee)\ ELSE\ MAX\big(Minimum\ Required\ Fee,$ $MIN(Water\ Fee + Accepted\ Fee\ Change, Current\ Year\ Fee\ Ceiling)\big)$
Description	It is the new value that the $Water\ Fee$ is to attain. If the current $Water\ Fee$ is greater than the proposed new fee then the change is implemented. In case an increase in $Water\ Fee$ is needed to bring it up to the value of $Required\ Fee$ than the increase does not necessarily get implemented and is subject to modifications. So that the resulting $Water\ Fee$ does not have to exceed the $Current\ Year\ Fee\ Ceiling$ nor the value acceptable to the consumers. However, regardless of these constraints on water fee increase, it does have to increase, if needed, to at least the value of $Minimum\ Required\ Fee$.

Reference for definition of independent variables	
$Required\ Fee$	Object C5.50
$Water\ Fee$	Object C3.1
$Minimum\ Required\ Fee$	Object C5.53
$Accepted\ Fee\ Change$	Object C5.55
$Current\ Year\ Fee\ Ceiling$	Object C5.54