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

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Abstract

This paper presents the development of a system dynamic model for the sustainability assessment of strategic asset management plans for municipal wastewater collection systems. A causal loop diagram is constructed to present the links between sewer-network and sewage-treatment-plant systems and to depict the feedback mechanisms existing between physical, financial, and consumer sectors. Then, the presented cause-effect chains are mathematically parametrized and modeled in the novel system dynamic model. Unlike other sustainability assessment tool, this one captures the non-linearities and variations in the energy footprints of wastewater-collection and -treatment services, as well as both the positive and negative impacts on upstream and downstream processes.

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

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

1 Introduction

This section describes the motivations and objectives in this research and review the previous models related to asset management planning of water and wastewater infrastructure systems.

1.1 Motivations

Sustaining municipal wastewater treatment systems in good condition is essential for citizens' health and safety in urban environments. However, ageing Wastewater Collection (WWC) pipe networks and reactive maintenance planning have caused accelerated deterioration of sewer network systems. The cost of replacing deteriorated pipes has been estimated at more than 25 billion dollars according to the Canadian Infrastructure Report Card (2016), and the problem is a complex one, with social, economic, environmental and technical ramifications.

Over the past decades, several regulations and guidelines have been passed by federal and provincial governments to guide utilities toward sustainable planning of municipal wastewater systems. The Water Opportunities and Water Conservation Act (WOWCA 2010) asked municipalities to prepare long-term asset management plans and secure financial resources for their future reinvestments needs. Asset management plans is defined as "the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems over their lifecycles" (PAS 2008).

Such a plan should comply with former regulations and guideline such as the Green Energy Act of (2009), which also requires public agencies, including municipalities, to prepare an energy conservation and efficiency strategy when planning their capital investments. Additionally, there is Ontario Regulation 452/09 (2016), which requires reporting from facilities that annually emit more than 25000 tonnes of GHGs; therefore, over 300 municipalities in Canada have joined in the Partners for Climate Program (PCP) to take local actions to reduce the GHG emissions from their operation and services, including water and wastewater infrastructure.

Complying with existing and changing regulatory policies and requirements, and developing socially acceptable, environmentally friendly and financially viable asset management plans is a major challenge involving integration of various disciplines such as finance, planning, and engineering. The complexity of planning decisions is compounded when planners realize that the different economic, social, and environmental dimensions of the challenge are inherently interrelated. Several tools and frameworks have been promoted for the Sustainability Assessment (SA) of water and wastewater asset management plans. However, the system dynamics of urban water and wastewater system and its importance for complete Sustainability Assessment (SA) are not considered in current approaches (Upadhyaya 2013).

1.2 Research background

SD has often been applied as a convenient simulation tool for modeling the socio-economic impacts of strategic decisions on water resource management problems (Mirchi et al. 2012). Recently, the SD tool is been used to model the complexity of water and wastewater infrastructure systems. Chung et al., (2008) applied SD tool to model water sources, users, recharge facilities, and water and WWTPs as subsystems for general water supply planning, and to calculate the construction, operation and maintenance costs of water and WWTPs. Biachia and Montemaggiore, (2008) integrated SD with the Balanced Scorecard approach to analyze the dynamics and interdependencies between key financial indicators and intangible variables such as the customer satisfaction, business image, bargaining power of a water utility company.

Ganjidoost (2016) have developed a framework that models the feedback mechanism of integrated water distribution and WWC network systems, using the SD modeling approach. His model has been built on studies Rehan et al. that 1) in 2013, applied the SD tool to model urban water distribution systems, and 2) in 2014, developed an SD model to evaluate the financial sustainability of urban WWC system. Various interconnections and feedback between the physical, financial, and social systems related to the linear water and wastewater infrastructure were modeled in their research.

SD modeling is also being used as an optimization technique for designing WWTP systems ─ see studies done by Das, Bandyopadhyay, and Mohapatra (1995), Gillot et al. (1999), and Parkinson, Schütze, and Butler (2005). Their models demonstrate the dynamics and complexity of wastewater treatment systems and present the feedback mechanisms between different components of a WWTP system at the operational level.

A complete model of an integrated water and wastewater infrastructure system should include both the linear water distribution and WWC networks and the non-linear water and wastewater treatment systems, as illustrated in Figure 1. Previous SD models have only considered the linear water and/or wastewater network system (s), leaving the cost of sewage treatment as an exogenous factor. Ganjidoost (2016) has shown how upstream water distribution systems affect sewage collection systems based on the extraneous infiltration from leaky water distribution pipes. This present study is the first attempt to model the integrated sewage-collection and sewage-treatment systems at the strategic level.

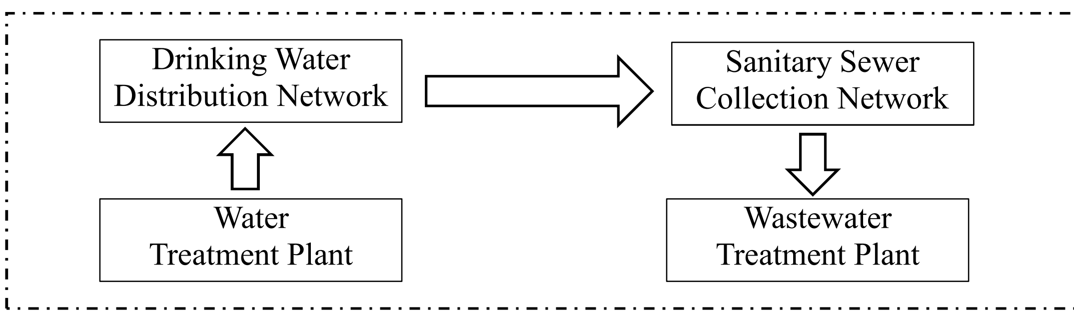


Figure 1: A complete water and wastewater infrastructure system

1.3 Objectives

The main objective of this research paper is to demonstrate the application of SD tool for the SA of WWC asset management plans. A complete SA, as described by Sala, Ciuffo, and Nijkamp (2013), should assess all dimensions of sustainability, i.e., economic, social, environmental; deal with non-linearities and dynamic features, and include the consequences on upstream and downstream processes, i.e., water distribution and Wastewater Treatment Plant (WWTP) systems respectively. This study is built upon the Rehan et al. (2014) SD model, developed for asset management planning of linear WWC systems; several additional modules are developed here to model the interactions and feedback between the WWC and WWTPs, and to demonstrate the application of SD for a complete SA. First, a novel SD model for simulating of WWTPs' physical and financial performance is modeled and then integrated into the WWC asset management planning model. Second, an energy footprint module, as a proxy for the environmental sector, is developed and added to demonstrate the application of SD model for environmental SA. Moreover, the original physical, social, and finance sectors of the WWC asset management planning model are edited to account for the effect of population and urban area development.

2 SD modeling

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

2.1 Causal-loop-diagram development

Identifying the driving forces needed to develop the cause-and-effect-chain mechanism in a system occurs in the early stages of SD modeling. Such qualitative relationships among the variables are first identified in a Causal Loop Diagram (CLD), then parametrized in the SD model. A plus (+) or minus (-) sign is used to represent the positive or negative influence of a variable. A positive link indicates that a positive/negative change in one parameter will cause a similar subsequent positive/negative change in the linked parameter. In contrast, a negative link indicates that the linked variables are conversely related to each other, so that a positive/negative change in one variable will result in a negative/positive change in the dependent variable. Two feedback loops are identified in the CLD: The reinforcing loops, which represent positive feedback, shown by "R", and the counteractive balancing loops, is shown by "B".

Figure 2 presents the CLD of the SD model for WWC and WWTP systems. The total inflow volume received by the WWTP depends on the volume of Inflow and Infiltration (I&I) entering into the sewer network system, and the volume of sewage generated by system users. The infiltration rate to the sewer network system increases as sewer pipes deteriorate and their internal condition grade increases. Sewage generation is increased by population growth factor which is also affecting the I&I flow rate due to sewer network expansion in urban area developments. The consequence of an increasing inflow volume is an increasing cost of operating WWTPs, and the need for capital investment to expand capacity. In contrast, it is assumed that decommissioning a WWTP will cause no major capital cost. Construction and operation of new WWTP capacities as well as the new sewer network installation and operation cause the increase of energy footprint of sewage collection and treatment services to consumer.

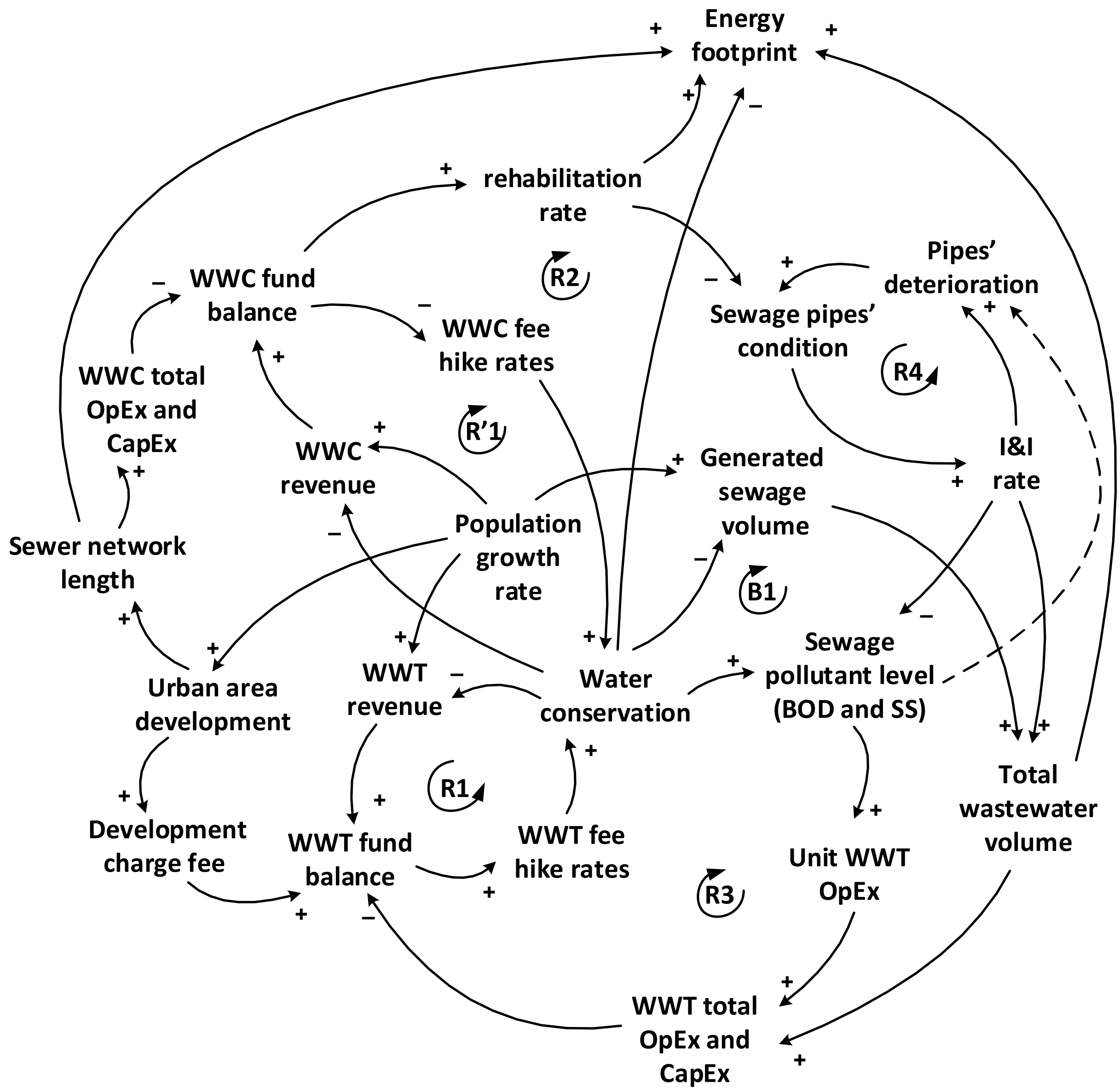


Figure 2: CLD model of wastewater treatment plant system

To increase the fund balance, utilities need to increase revenues by increasing system users' fees. As sewage collection and treatment fees are directly tied to the metered volume of water, users' response will be water-demand reduction and water conservation which will decrease the energy footprint by reducing the energy use in upstream water treatment and water distribution systems. On the other hand, population growth will increase the user-fee based revenues of WWC and WWT utilities. Development charge is another revenue stream of utilities which is collected to cover the required capital work expenses due to urban area development.

The reinforcing loops (R1) and (R'1) show that users' water conservation efforts result in decreasing revenues and less available funds for utilities. The second reinforcing loop (R2) shows that the increasing WWT fee reduces the funds available for reinvestment and rehabilitation of the sewer pipes, which in turn, leads to further deterioration of a sewer's condition and increased I&I to the WWTPs.

The third reinforcing loop (R3) shows the cause-and-effect-chain mechanism that exists between water conservation, sewage pollutant level, operation and maintenance costs of the WWTP systems, fund balance, and sewage-fee hikes. The water conservation, as well as the I&I reduction will increase pollutant concentrations in wastewater. Marleni et al. (2015) have demonstrated that the water-use reduction in various water-demand management scenarios increases the concentration of sulphide and sulphate levels by 30% and 40% respectively. These two compounds, which are the main source of hydrogen sulphide formation, will cause odor problems and corrosion of sewer pipes. This is shown by a dashed line to imply that the causal link is not implemented in the model.

In another study, Parkinson, Schütze, and Butler (2005) reported the increased concentration of Suspended Solids (SS) and Biological Oxygen Demand (BOD) in wastewater as a result of water-conservation scenarios. Min and Yeats (2011) have shown that an increase of the BOD and SS level increases the unit-operational and maintenance costs of both sewer and sewage treatment per cubic meter of collected and treated wastewater.

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

Finally, the fourth reinforcing loop (R4) shows the acceleration of pipe deterioration rates by increasing I&I flow rate through worsening the pipes' condition. The Balancing loop (B1) shows that the reduction of total wastewater volume from water conservation will lower the operational and capital expenses and help to increase the fund balance. The increase of the fund balance will reduce the service fee increase rate, leading to a drop in water conservation practices by consumers.

2.2 SD model development

In this chapter, an SD model representing the financial, social, and physical sectors is presented. The SD model is developed using the research version 9.1.4 of Stella® software (Richmond 1997).The four basic elements, as in any SD model, are the stock, flow, converter, and connector all shown in Figure 3. "Stocks" represent the accumulation of physical or non-physical elements in a system, i.e., the total available treatment capacity. "Flows" are used to model the inputs or outputs to the stock, and represent the activities in a system, i.e., the wastewater inflow to the treatment plant. "Converters" are used to incorporate the effects of changing variables in an SD model. "Connectors" represent the links between the convertors, stocks, and flow components of an SD model.

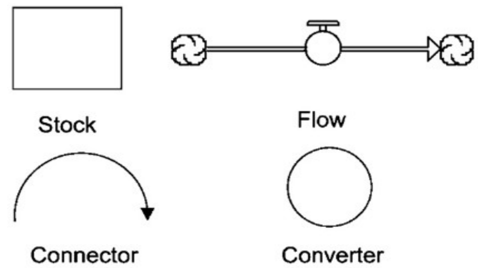


Figure 3 Basic elements in SD modeling

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

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

2.2.1 Consumer Sector

Consumers' reactions to an incremental change of their wastewater service fees are modeled in this sector based on the model described in Rehan (2011). The daily water-use per capita or water demand is estimated as a function of the price elasticity of demand, the user fee, and the minimum water demand (Figure 4). The price elasticity of demand, which is the percentage change in water demand per corresponding percentage change in the fee, is 0.35 in Rehan et al. (2015). The minimum water demand is considered to be 150 liters per capita per day (lpcd) in Ganjidoost (2016).

In this study, the modeling of the consumer sector is improved by decoupling non-residential and residential users, as well as developing the population growth model. In the Rehan (2011) and Ganjidoost (2016) models, water demand is calculated as the sum of residential, commercial, institutional and industrial water demand divided by population under the assumption that all customers experience the same price elasticity of water demand. However, this assumption is too simplistic because industrial users can often apply technological means to reuse and conserve water and significantly cut their water demands. Water and wastewater utilities also set different price rates for non-residential users in consideration of their social and economic importance to the societies who are depending on them.

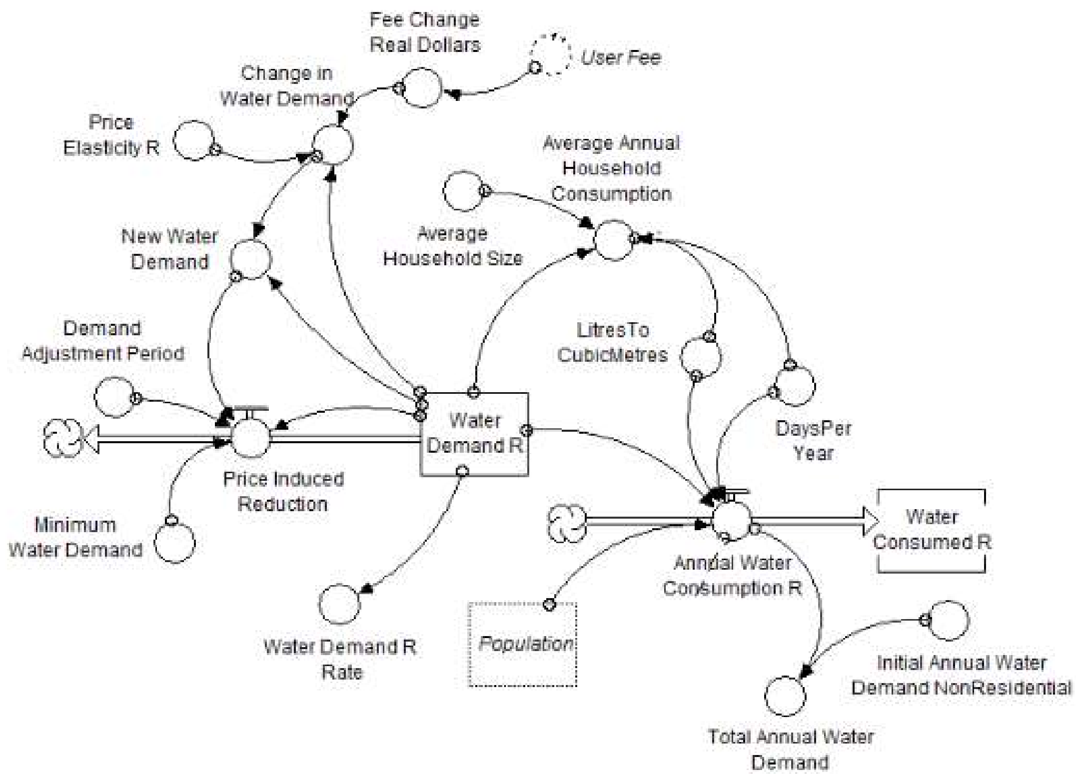


Figure 4: Consumer water demand change

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

Population growth is been developed by integrating a 0 to 100 percent urban densification index to model various urban development scenarios. In extreme densification, new population is served within the current sewer network which avoids the installation and operation of new pipes to WWC utilities. It also does not impact the WWTP systems' operation and capacity planning due to future I&I increases to the sewer network. In contrast, the extreme urban development scenario requires a growing sewer network—at the same rate as the population growth—which would incur capital and operational costs for both the WWC and WWTP utilities, and intensify the energy footprint of wastewater-collection and -treatment services. The impacts of urban densification on the WWTP finance sector and environmental energy sector are described further in Section 2.2.3 and Section 2.3 respectively.

2.2.2 Physical infrastructure model

The physical sector consists of a brief review of the sewer network model of (Rehan 2011), followed by the new model development for the WWTP system.

2.2.2.1 Sewage collection pipes model

Pipe inventories are made up of different pipe materials such as vitrified clay, concrete, Polyvinyl Chloride (PVC), ductile iron, etc., and are grouped into five classes, which are represented in Figure 5 as stocks, based on their Internal Condition Grade (ICG) defined by the UK Water Research Center (WRc 2011). The method used in Rehan et al. (2014) is adapted to define the deterioration and infiltration rate.

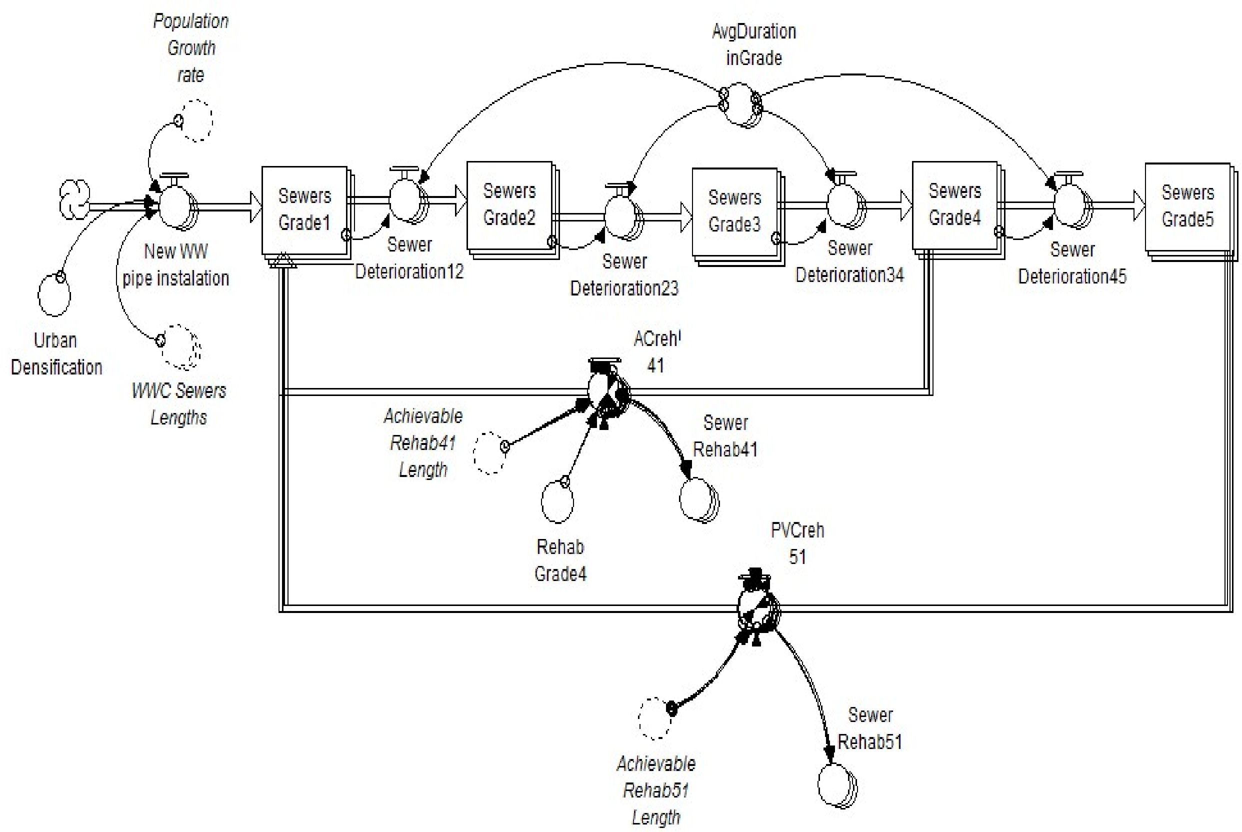


Figure 5: The sewer collection network model

New pipes with the best ICG are in the first stock class, whereas pipes in the worst condition belong to the fifth stock class. Today, PVC pipes are used in new pipe installation projects. Therefore, the new pipes –either for replacing the ICG5 stock or for urban development and network expansion, and the rehabilitated ICG4 pipes are entering to the first PVC pipe's stock.

2.2.2.2 WWTP capacity model

WWTPs' physical assets consist of electromechanical equipment, such as pumps, motors, aerators, mixers, tanks, basins, pipes, and buildings. Modeling of the functional relationship of these parts has been done at the operational level for the efficiency increase of WWTPs. As shown in Figure 6, the modeling of WWTP assets in this model is done at a high level based on the WWTP's total capacity. The WWTPs' capacity requirement is equal to the sum of estimated sewage generation from residential and non-residential users and the I&I flow. Sewage generation rates depends on population growth rate and water demand rates, and the I&I rate depends on the sewer pipes' condition.

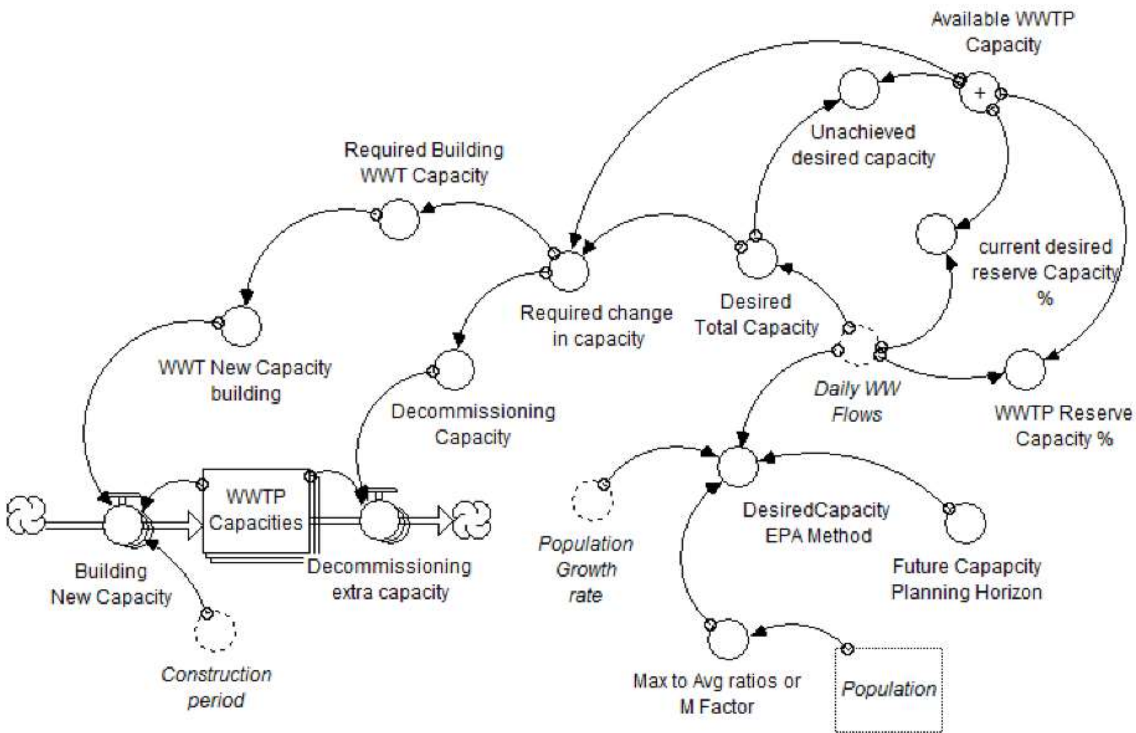


Figure 6: Changing the WWTP capacity

The reserved capacity for the maximum seasonal, daily, and hourly peak sewage flow can be estimated based on two methods: 1) the current reserve capacity of the WWTPs, or 2) based on the recommended standard defined by the Great Lakes-Upper Mississippi River Board (2014). A minimum 0.5 million-liter-per-day unit capacity is considered for building or decommissioning WWTPs' capacities.

2.2.2.3 I&I calculation model

The annual I&I volume is one of the main factors in calculating the WWTP capacity change requirement, as well as estimating the BOD and SS concentrations. Accurate calculation of initial I&I, which is used to determine the future I&I rate to the system, is particularly important. Two standard methods for calculating the initial I&I, from using the WWTPs' daily operational reports, are described in this paper. The annual I&I volume can be calculated by one of the two methods recommended by the U.S. Environmental Protection Agency (EPA) (2014). Both methods can be used to validate the I&I estimation.

In the first method, the average minimum sewage flow recorded at the WWTP during a dry weather period (7 to 14 days before the rainy season starts and when the ground water level is high) is used as the Groundwater Infiltration (GWI) rate. The Basic Sanitary Flow (BSF) is derived from subtracting the GWI from the average sewage volume for the same period of the reported year. The BSF is then subtracted from the annual average sewage flow in the reported year to estimate the infiltration rate.

$$\textit{Infiltration} = \textit{Avg. annual sewage flow} - \textit{BSF} \tag{2}$$

$$\textit{BSF} = \textit{Avg. dry weather sewage flow} - \textit{GWI} \tag{3}$$

In the second method, the BSF is calculated by subtracting the average volume of consumed water from the average volume of metered water (for a period of time before outdoor recreational activities start). The consumed or evaporated water represents the amount of metered water that has not been discharged to the sewer network after use. The infiltrated ground water volume is calculated by subtracting the BSF from the annual average sewage flow at the WWTPs in the reported year. The volume of inflow can be estimated by subtracting the BSF and infiltration volumes from the inflow volume to the WWTP for the days with reported precipitation.

2.2.2.4 Sewage composition model

The concentration of SS and BOD is assumed to increase proportionally with declining sewage volume flowing into WWTPs. The unit mass of BOD and SS per capita is assumed to be fixed in time and is calculated based on the annual mass of BOD and SS reported by the WWTP divided by the current population. Thus, the concentration of SS and BOD changes as the generated wastewater ─which is a function of the Water Demand (WD) and the Consumptive Use Fraction (CUF) of metered water─ and I&I change over the simulation period. The BOD and SS models are presented in Figure 7, and their concentration are formulated as in the following 4 and 5 equations.

$$SS\,(t) = \frac{Initial\,(SS) \times\, population(t)}{365 *\, WD(t) * (1 - CUF) \times popuation\,(t) + I\&I\,(t)} \tag{4}$$

$$BOD\ (t) = \frac{Initial\ (BOD) \times\ population(t)}{365 *\ WD(t) * (1 - CUF) \times popuation\ (t) + I\&I\ (t)} \qquad (5)$$

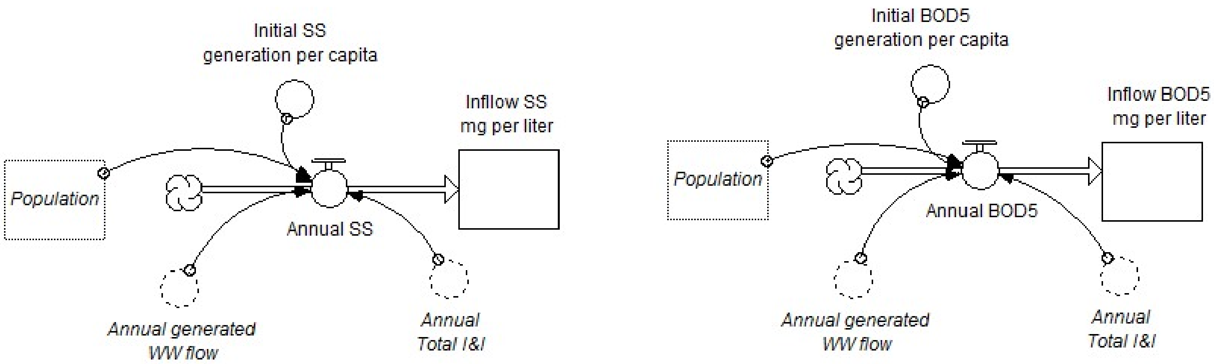


Figure 7: The BOD and SS concentration change model

2.2.3 Finance sector

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

2.2.3.1 Sewage collection network finance model

The operation and maintenance cost of pipes in different ICG categories and the residential user fee calculation are modeled similar to the Rehan (2011) model. The new parts of the model consist of separate fund balance stocks, named as the *WWC Operational Fund Balance* and *WWC Capital Fund Balance*, and a cash reserving stock which is shown as *WWC Cap-CashReserve* in Figure 8. The user-based revenues generated from the *WWC fee* and the monthly *WWC Service Charges* are primarily allocated to pay the *WWC Maintenance Expenses* and the *Debt Services*. The remaining is saved to the capital fund balance for paying the capital costs for rehabilitation and expansion of the sewer network. The WWC utility has the option to issue debt to maintain a zero capital fund balance if the cascaded revenue from operational fund balance is not sufficient to pay the capital expenses. In the opposite scenario, it can reserve the surplus revenue for future lump capital expenses. Separation of the two fund balance accounts, plus the new model structure, restrict the issued debt and reserved cash from paying the operational expenses.

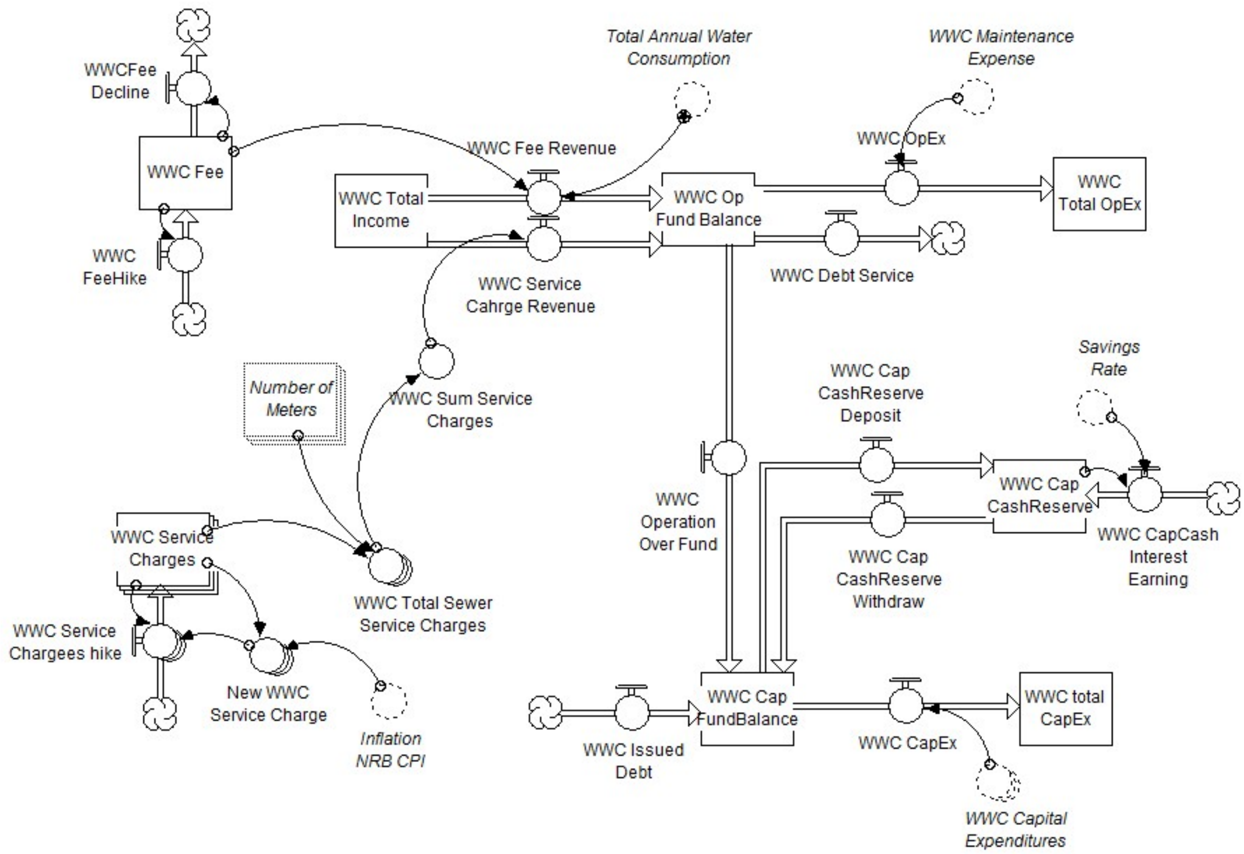


Figure 8 WWC finance model

2.2.3.2 Sewage treatment plant finance model

A novel finance model, with two key interconnected but separate stock-flow structures, 1) the hierarchical fund balance, and 2) user fee and development charge stocks, is developed for the WWTPs finance sector. As shown in Figure 9, the hierarchical fund balance structure consists of the *WWT Operational Fund Balance, WWT Development Fund balance*, and *WWT Capital Fund Balance*. For the operation fund balance, the sources of income are the wastewater treatment user fees and the over-strength charges. After paying for operation expenditures, similar to the WWC finance structure, the surplus revenues are available to be cascaded to the lower fund balance stocks. The income of the *Development Fund* comprises *Development Charges* received from new residential and non-residential developments. If the utility has debt, it will pay the *Debt Service* first, and then the surplus becomes available for cascading to the *Capital Fund Balance*.

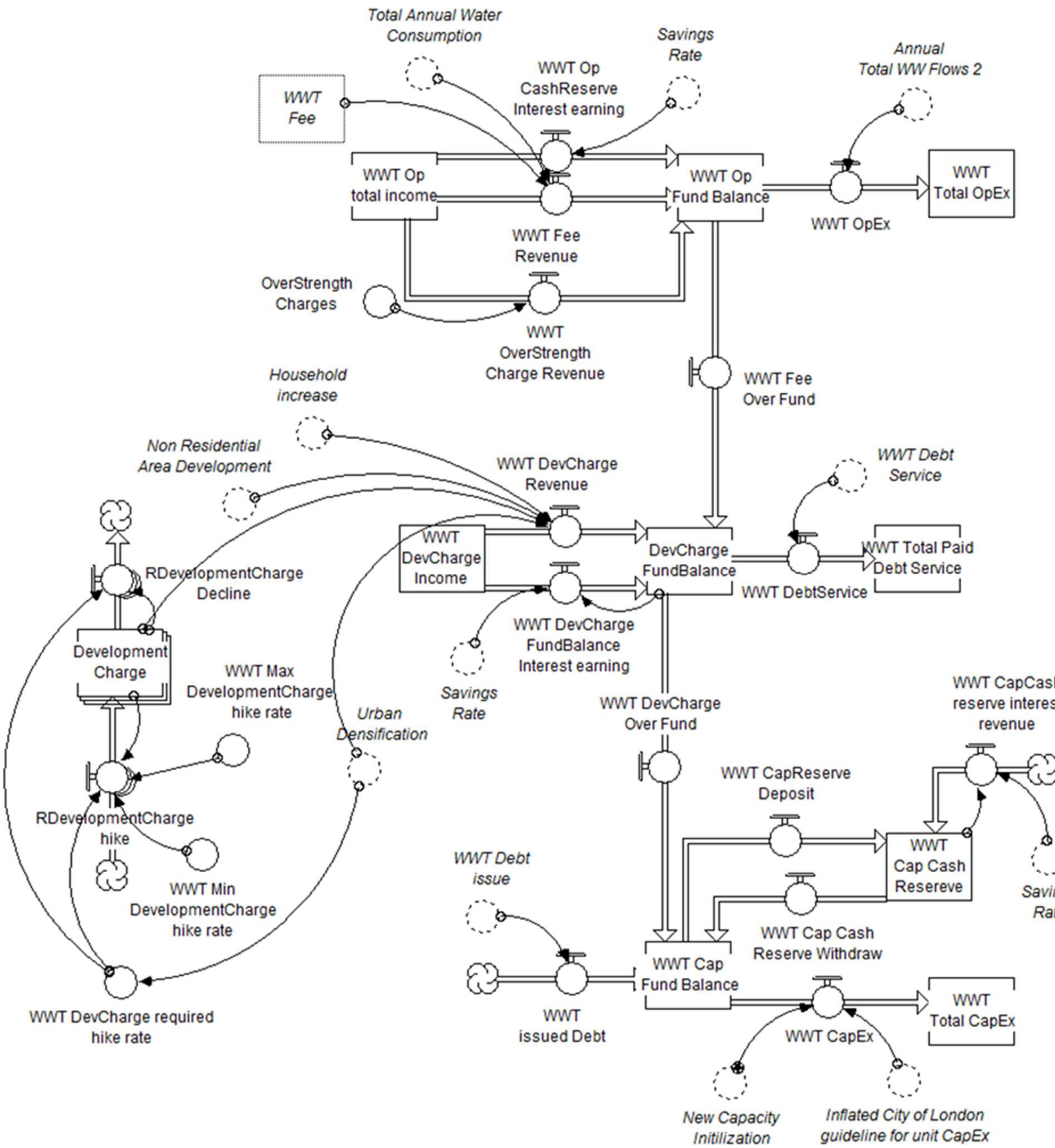


Figure 9 WWT finance model

After spending on WWT capital expenditures, the stakeholders will have the option to do cash reserve from 0 to up to 50% of the total treatment plant replacement value. If the capital fund balance is insufficient for capital works, the utility has the option to issue debt to maintain zero fund balance. It should be noted that the flow of revenues from higher fund balance stock only happens when the revenues in lower stock are not sufficient to pay the expenses. Otherwise, the revenues will be accumulated in their corresponding stocks.

The *WWT Fee* is calculated as a unit cost of wastewater treatment per cubic meter of treated wastewater when a pay-as-you-go strategy is adopted. In other financial strategies, such as borrowing or capital reserving, the debt service cost and the required cash for building the cash reserve account are integrated with the cost of wastewater treatment to calculate the required cash to be generated from the WWT user fee.

Development charges are due when there are new building permits issued, and they create a major source of income for the wastewater capital cash flow. With a 0 to 100 percent urban densification index (I), there are two extreme scenarios in the development charge sector. When there is 0 percent urban densification, the model assumes that only single houses and townhouses can be built. In contrast, the model assumes that only apartments and lodging units can be built when the unban densification index is set to 100 percent. The residential development charge is calculated using equation (6).

$$DC_{residential} = N_{residential} \times [(1 - I) \times S + (I * A)] \tag{6}$$

where DC stand for the development charge, N denotes the number of residential households increasing per year, the term I represents the urban densification index (%), S is the average value of residential wastewater development charges for single houses and townhouse, A represents apartments and lodging units. The development charges for non-residential units ─commercial, industrial and institutional─ are established based on their area. The total development charge is the sum of the residential and non-residential development charge. Table 1 shows the initial unit development charges for different types of buildings which is reported by regional municipality of Waterloo (2017).

Table 1Initial Unit Development Charges

Apartment & Lodging	2225 ($)
Townhouse & Semi/Single	4570 ($)
Non-residential	2.19 ($/ft^2)

Similar to the WWT user fee, new policy levers are designed to control the maximum and minimum development charge hike rates. Defining the upper and lower bound will control impractical swings in simulations for the user fee and development charge hike rates.

2.2.3.3 Operational and capital expenses of WWTP systems

This section describes the models for calculating the Capital and Operational expenses at WWTPs. The CapEx is the required investment costs for building or expanding the required

WWTP capacity calculated in the physical sector. The U.S. EPA (1980) methodology, as well as the utilities' self-reported guidelines, can be used for estimating the unit CapEx.

$$\begin{aligned}&Capital\ cost\ for\ new\ capacity\ construction\ (CAD)\\&= MAX\left[0, Current\ treatment\ capacity\ \left(\frac{m^3}{day}\right) - 1.5\right.\\&\left.\times \left(I\&I\ flow\left(\frac{m^3}{day}\right) + Sanitery\ sewage\ flow\ \left(\frac{m^3}{day}\right)\right)\right] \times 2950\ (CAD/\frac{m^3}{day})\end{aligned}$$

The OpEx consists of four major cost elements: the employee or manpower cost, utilities cost, chemical and material costs, and maintenance costs. Figure 10 shows the average proportional share of these elements, calculated based on the last seven years of reported annual financial expenses of a WWTP in the City of Toronto. A similar approach and results can be found in the study done by Tsagarakis, Mara, and Angelakis (2003).

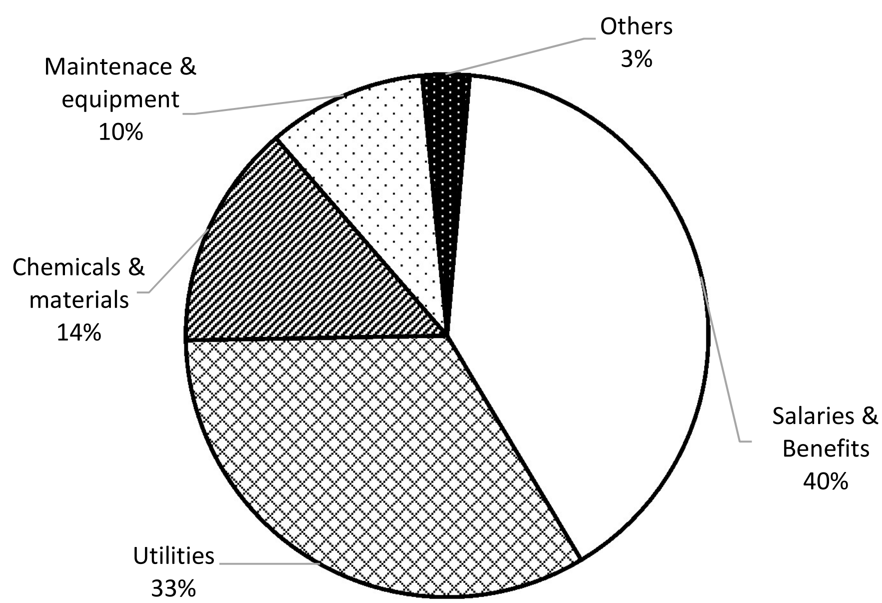


Figure 10: Average annual WWTP operational cost of Highland Creek WWTP-City of Toronto

Several survey studies have been conducted to develop mathematical models for predicting the operational cost of WWTPs. Hernandez-Sancho, Molinos-Senante, and Sala-Garrido (2011) have parametrized the OpEx and CapEx based on the sewage flow rate, contaminant removal rate, and the age of WWTPs, by analyzing 341 Spanish WWTPs' data. Their regressed function demonstrates the increase of the OpEx in seven types of sewage treatment technologies with an increase in the age and SS removal rate.

Balmér and Mattson (1994) have studied 20 homogenous WWTPs in Sweden to assess the manpower, electricity, chemical, and maintenance costs of the sewage treatment plants against the increasing population equivalent ($P_{eq.}$ is defined by the European Commission-Environment (2007) as an equivalent population of loading 60 grams per day per capita BOD in the sewage system). Their analysis shows a declining trend in the unit cost of electricity, manpower, and maintenance, and a fixed unit cost of chemicals by increasing P_{eq}. Fraas and Munley (1984) have proposed a function for predicting the marginal OpEx and CapEx of sewage treatment plants for increasing sewage volume and BOD concentration by analyzing 178 WWTPs in the United States. Their model predicts an exponential growth in the unit OpEx of sewage treatment with increasing inflow volume and BOD concentration.

Since the majority of WWTPs are not operating at their optimum condition (Hernández-Sancho and Sala-Garrido 2009), finding an accurate predictive function has not been possible to date. However, all the reviewed models support the idea of increasing the OpEx when the sewage SS concentration increases. Although these mathematical relationships can be applied for estimating the WWTP OpEx, it would be more relevant and intuitive to use the existing financial data found in the WWTPs' reports, and develop some first-order relationships for estimating the OpEx. The reviewed functions rely heavily on their own collected data and are not developed for the purpose of understanding the WWTP systems' behavior. Nevertheless, these functions can be used in conducting a triangulation validation process and comparing their results with the SD model.

It is reasonable to assume that the amount of polymer used for sludge thickening and dewatering (which contributes 60% of the total chemical costs) is a function of the SS concentration in the sewage. Similarly, the amount of natural gas used for sludge incineration (which contributes 99% of the total utility used costs) is directly related to the amount of dewatered sludge, which is a function of SS level as well. If zero SS is coming to the WWTPs, no or little sludge will be generated; thus, no polymer would be needed for sludge dewatering, and no natural gas would be needed for sludge incineration. Therefore, both the unit utility use cost and the unit chemical cost are functions of the SS concentration of the wastewater coming into WWTPs.

The number of employees and their salaries' do not change with the sewage composition, but they are functions of the treatment capacity or the volume of treated wastewater (Balmér and Mattson 1994). The maintenance cost for replacing or repairing machinery and equipment is considered to be an annual fixed cost.

$$\textit{Operational expenses} = \textit{Fixed cost} + \textit{Variable Cost} \tag{7}$$

$$\textit{Fixed Cost} = \textit{employee cost} + \textit{Maintenance cost} \tag{8}$$

$$\textit{Variable Cost} = \textit{Utility cost} + \textit{Chemical cost} \tag{9}$$

Figure 11 presents the first order relations of the chemical and utility use costs calculated for one of the WWTPs in the City of Toronto.

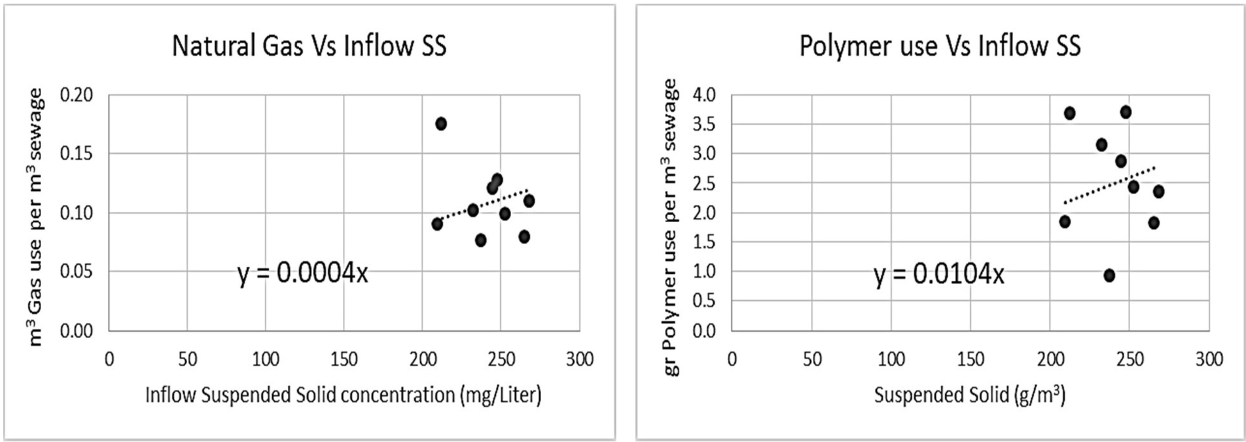


Figure 11: Unit cost of the polymers and natural gas per inflow SS concentration

2.3 Environmental Sector

The energy footprint indicator is calculated as a proxy for the environmental sector. From a life-cycle perspective, energy use accounting should be done for all life cycle stages of a studied product or service, including the manufacturing of materials, construction of structures, operation and maintenance of wastewater-collection and -treatment systems, rehabilitation and renewal of infrastructure parts, as well as disposal of waste materials and end-of-life components. The SD model is applied to capture the variations and dynamics in energy use due to the infrastructure's changing conditions and scales as a consequence of strategic decisions in asset management planning or population growth and urban area development.

Based on a study done by the United State Environmental Protection Agency (EPA 2014), more than 95% of energy use is attributed to the operational and maintenance stages of water and wastewater systems. Therefore, energy footprint modeling is centered on operation, maintenance, and rehabilitation activities. Figure 12 shows the different processes that are modeled and integrated to calculate the energy used for the collection and treatment of 1 cubic meter of wastewater generated by residential users.

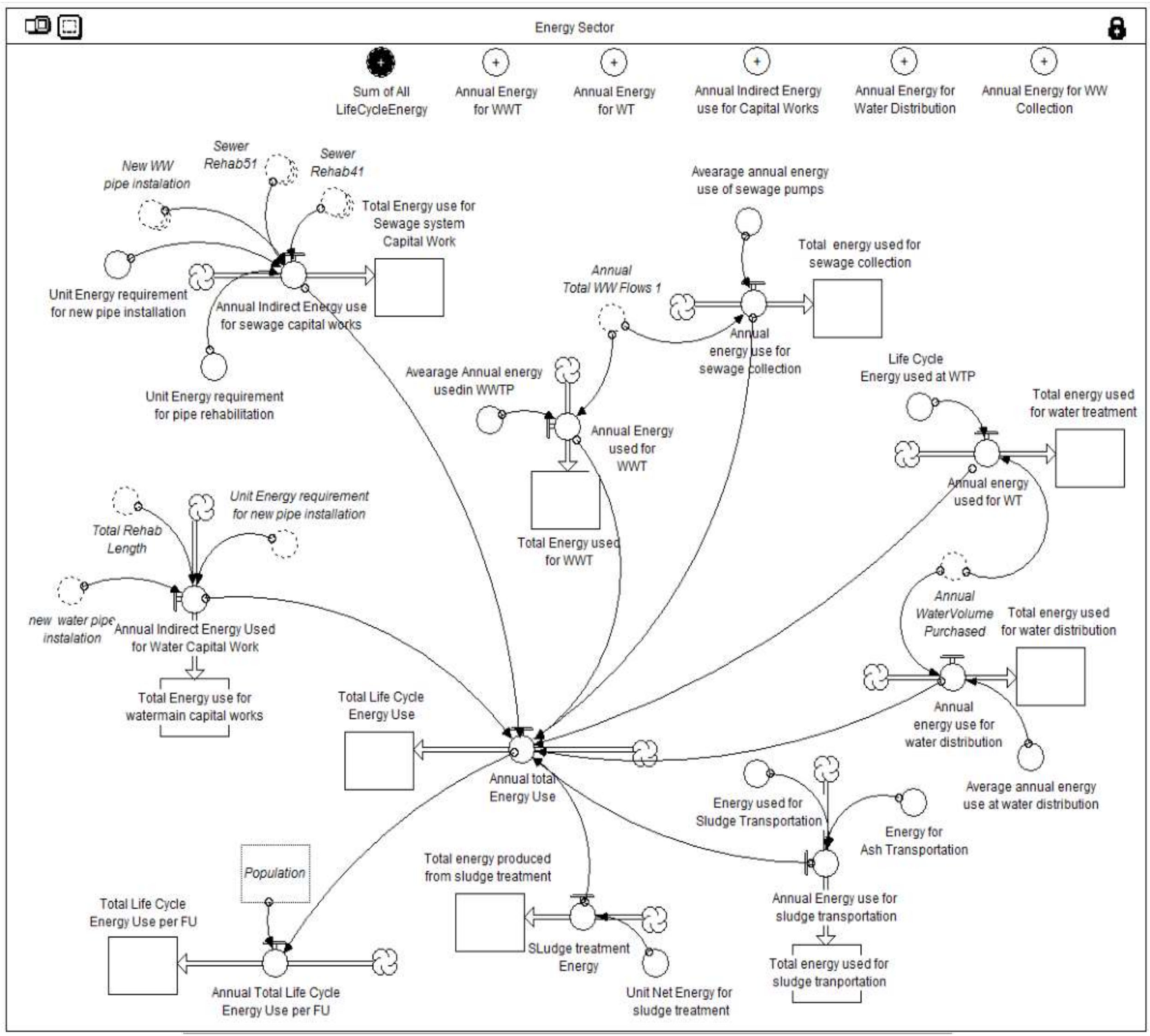


Figure 12 Energy sector model

3 Demonstration

The developed SD model is applied for sustainability assessment of an asset management plan for hypothetical sewage-collection and –treatment systems. Figure 13 shows a random distribution of assumed all PVC pipes in different ICG categories. The total network length is 1500 Km which serves 0.5 million consumers. The population growth is assumed to be 1.5% per year with 50% urban growth, and the initial total capacity of WWTPs is 250,000 m3/day.

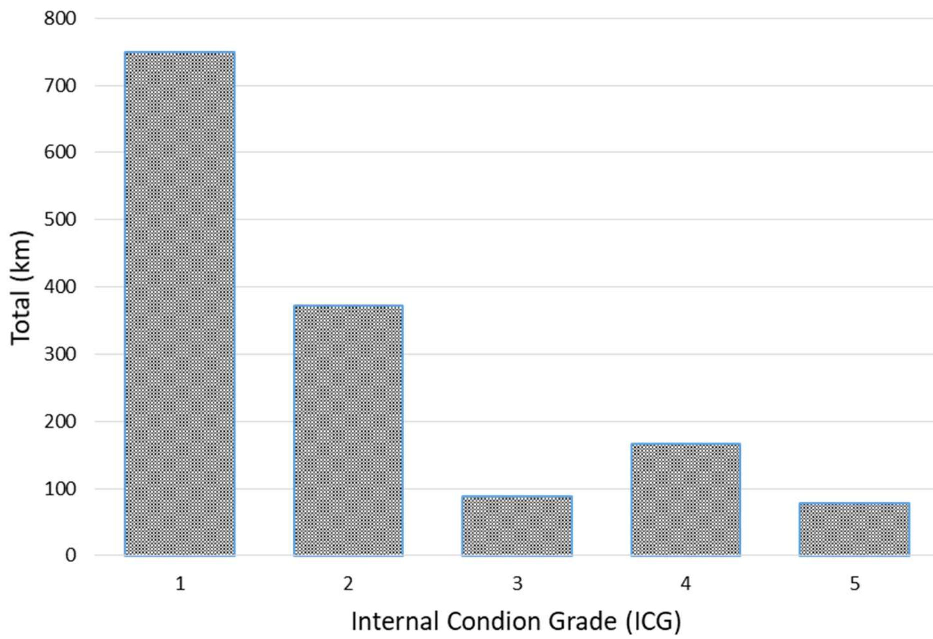


Figure 13 sewer pipes inventory

The police levers for maximum rehabilitation and WWC fee hike rate, as well as the maximum and minimum WWT fee and development charge hike rates are presented in Table 2.

Table 2 policy levers summary

Policy levers	*Pay as you go*
Preferred Max. rehabilitation rate (% of the network length/year)	1.3
Max allowable wastewater fee-hike rate (% per annum)	7.1
Max allowable wastewater treatment fee-hike rate (% per annum)	10
Min allowable wastewater treatment fee-hike rate (% per annum)	0
Max allowable Development Charge-hike rate (% per annum)	3
Min allowable Development Charge-hike rate (% per annum)	0
Max. acceptable fraction of Highly Deteriorated Pipes (ICG5)	10
Elimination period for Highly Deteriorated Pipes (ICG5)	10 years

Table 3 shows the energy use of the modeled processes.

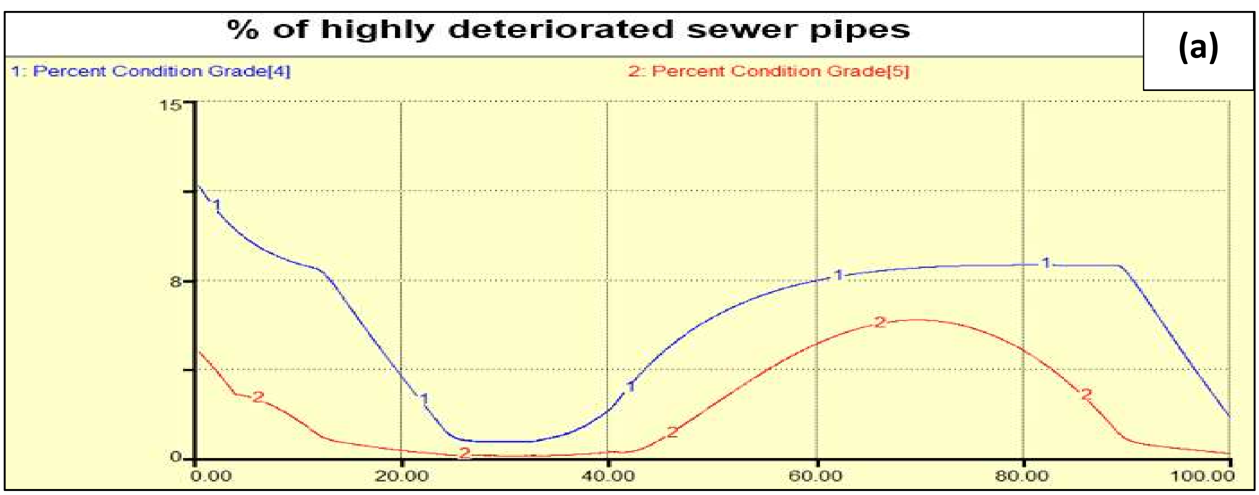
Table 3 energy use data inventory

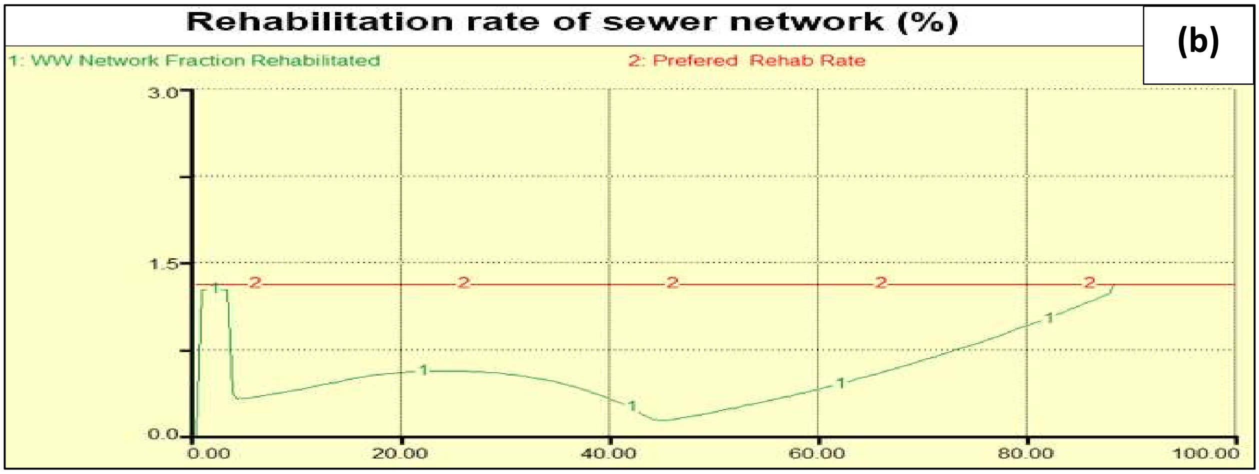
Energy use of processes that are accounted in the energy footprint assessment	*Value*	*Unit**	*References*
Life cycle energy used for PVC pipes manufacturing	75.2	MJ/Kg	(Du, Woods, and Kang 2012)
Life cycle energy use for drinking water treatment	2.4	MJ/ m^3	(Racoviceanu et al. 2007)
Energy use for water distribution	1.224	MJ/ m^3	From data sent by utility
Energy use for wastewater collection	0.23	MJ/ m^3	From data sent by utility
Life cycle energy used for wastewater treatment (including sludge transportation, incineration, and disposal)	1.55	MJ/ m^3	From data sent by the WWTPs
Life cycle energy used for pipe installation	405	KWh/m	(Prosser, Speight, and Filion 2013)

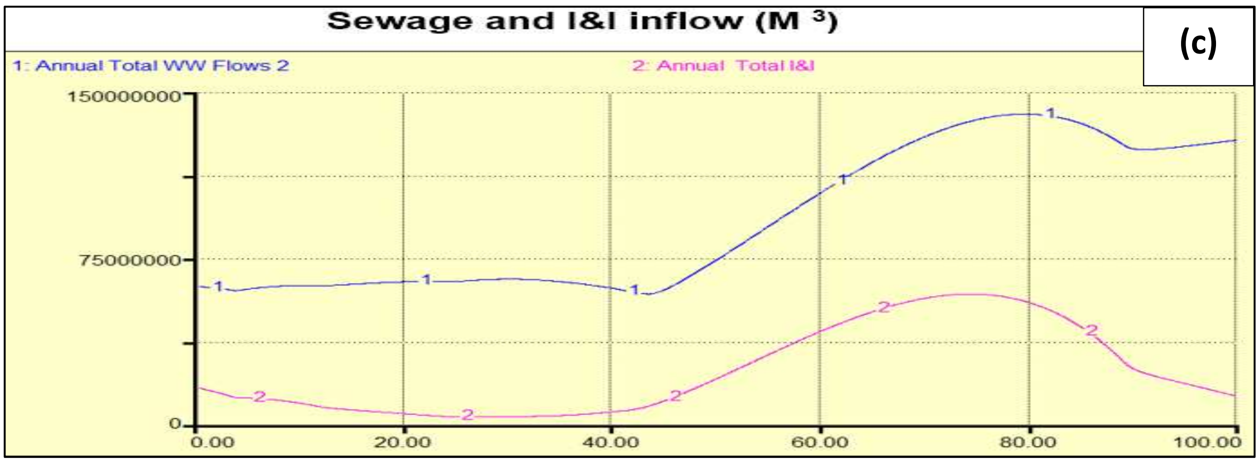
* MJ/Kg: Mega joule per kilogram, KWh/m: Kilowatt hours per meter

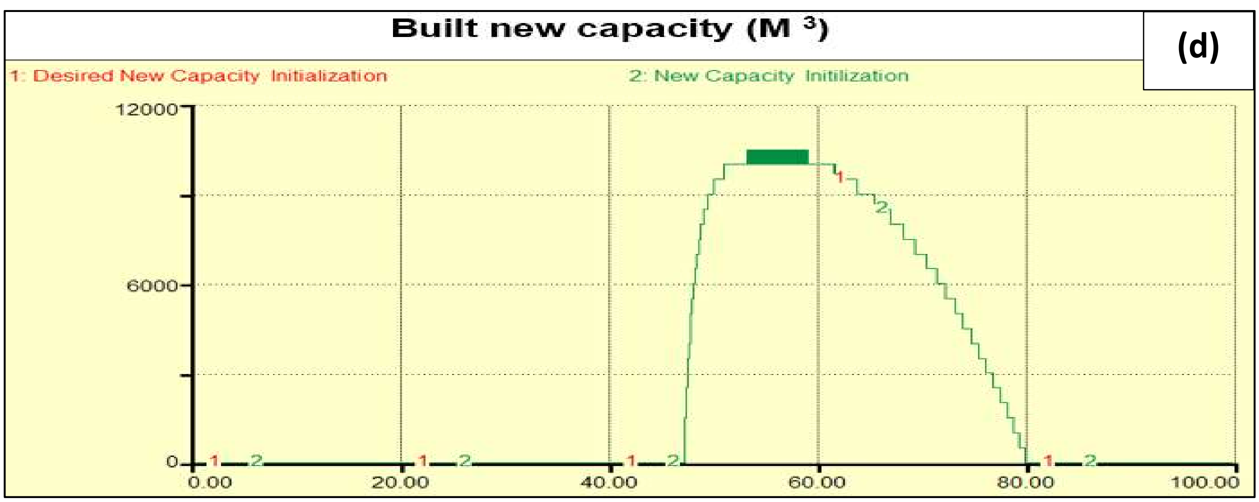
Slides (a), (b),(c), (d), (e), (f), (g) and (h) in Figure 14 are presented for the 100-years simulation of the strategic asset management plan.

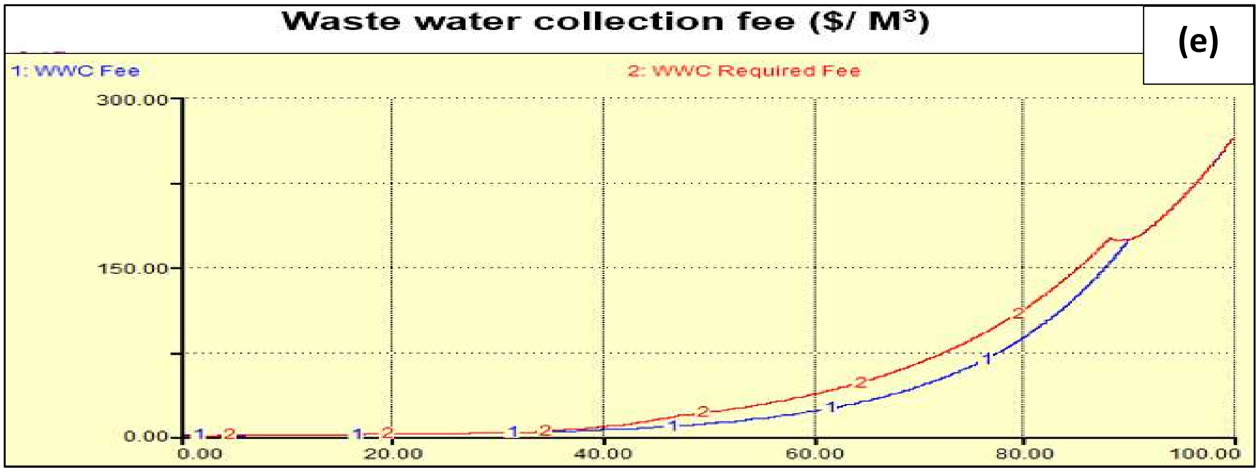
Figure 14 simulation results

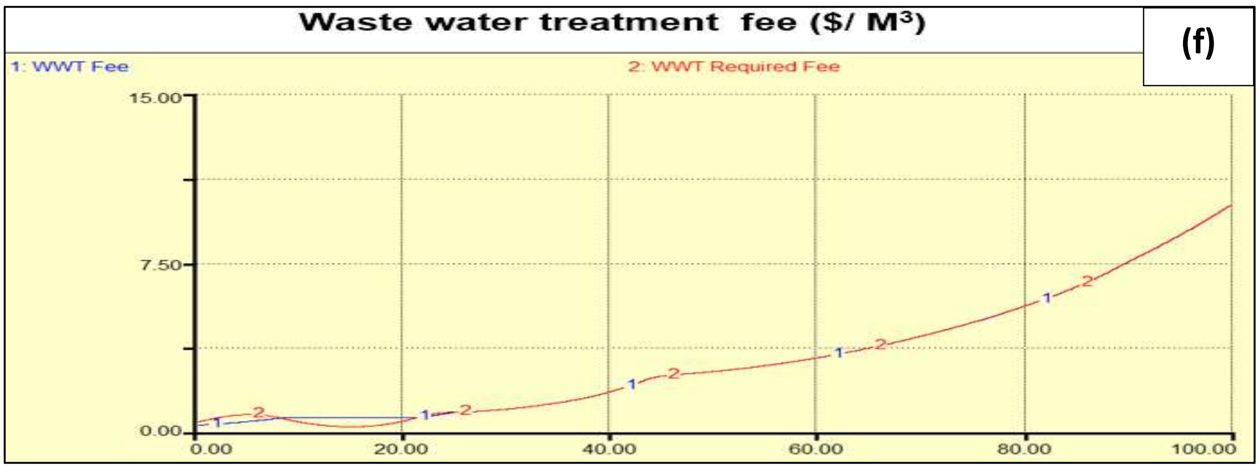


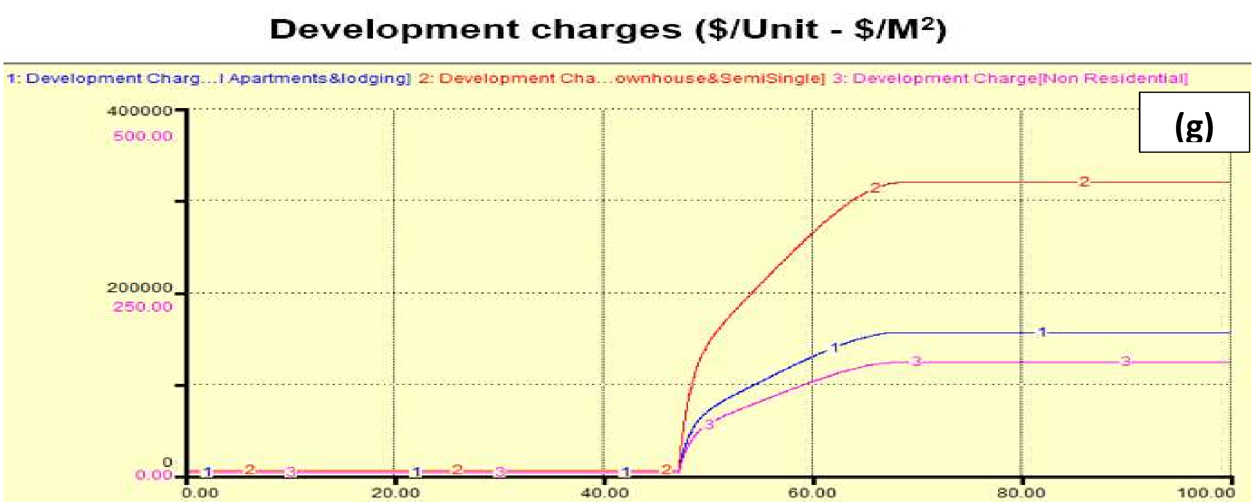

Rehabilitation rate of sewer network (%)
(b)
1: WW Network Fraction Rehabilitated
2: Prefered Rehab Rate
3.0
1.5
0.0
0.00
20.00
40.00
60.00
80.00
100.00

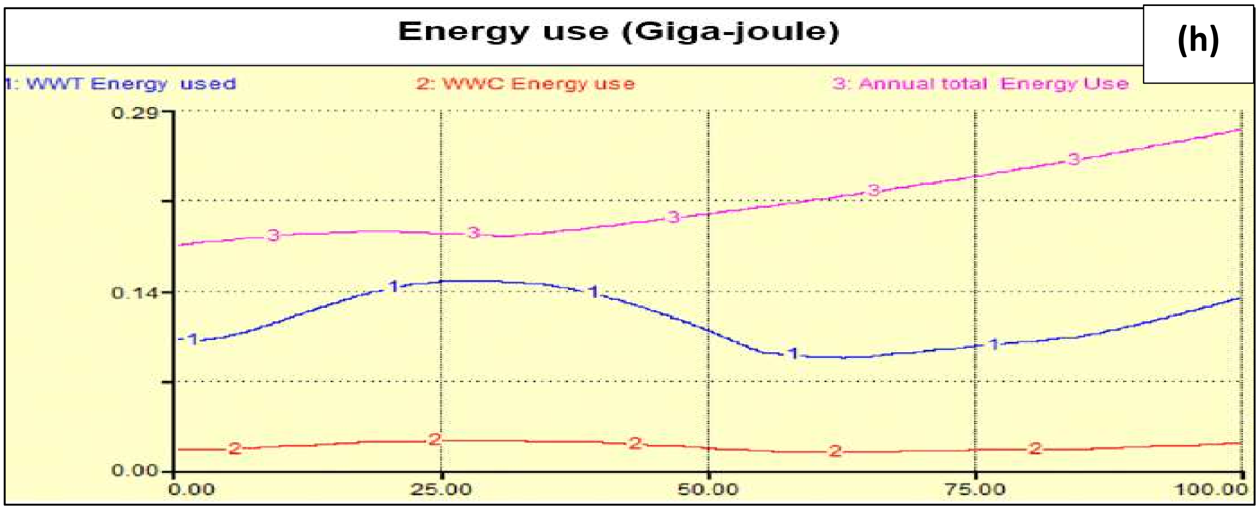

Sewage and I&I inflow (M 3)
(c)
1: Annual Total WW Flows 2
2: Annual Total I&I
150000000
75000000
0
0.00
20.00
40.00
60.00
80.00
100.00


Built new capacity (M 3)
(d)
1: Desired New Capacity Initialization
2: New Capacity Initilization
12000
6000
0
0.00
20.00
40.00
60.00
80.00
100.00


Waste water collection fee ($/ M³)
(e)
1: WWC Fee
2: WWC Required Fee
300.00
150.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00


Waste water treatment fee ($/ M³)
(f)
1: WWT Fee
2: WWT Required Fee
15.00
7.50
0.00
0.00
20.00
40.00
60.00
80.00
100.00


Development charges ($/Unit - $/M²)
1: Development Charg...l Apartments&lodging]
2: Development Cha...ownhouse&SemiSingle]
3: Development Charge[Non Residential]
(g)
400000
500.00
200000
250.00
0
0.00
0.00
20.00
40.00
60.00
80.00
100.00



4 Summary and future research

Wastewater from urban areas is collected in sewer networks and sent to treatment facilities. The WWC and treatment systems are directly linked to each other. Therefore, any change related to sewage network systems may have a direct impact on wastewater treatment plant (WWTP) systems. Securing funding for capital and operational expenses of WWTPs has the same, if not a higher priority, if sustainable wastewater infrastructure systems are to be achieved. Therefore, it is important to consider the interrelation and feedback mechanisms that exist between these two systems when planning for their financial sustainability.

As shown, the integrated wastewater-collection and -treatment systems constitute a complex system which can be modeled by using the system dynamics modeling approach. A complete system dynamics modeling of urban water and wastewater systems will include the integrated linear and non-linear infrastructure system, i.e., water distribution and sewage collection, as well as the water treatment and wastewater treatment systems.

Integration of system dynamic modeling and life cycle assessment perspectives will allow researchers and decision makers to evaluate the behavior of water and wastewater system and anticipate the consequences of decisions on when, where, and how to invest in infrastructure upgrading and installation. A complete analysis of a WWTP system may include other sources of pressure on the wastewater infrastructure systems, For example, the consequences of climate change impacts on water availability and increasing of flooding and drought intensity on the financial and operational performance of wastewater systems can be modeled.

Further research will be needed to model the impact of increasing sewer blockages and odor problems from water conservation practices, as well as the related impacts on consumers' willingness to accept sewage fee hikes. The presented model has included the physical, finance, environment, and consumer sectors. The scope of the environmental sector can be extended to include other environmental footprints, such as water and carbon footprints, to account for complete environmental sustainability of wastewater treatment systems.

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Reference

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

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

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

Canadainfrastructure. 2016. "Canadian Infrastructure Report Card: Informing the Future," 1–164.

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

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

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

DeZellar, Jeffrey T., and Maier Walter J. 1980. "Effects of Water Conservation on Sanitary Sewers and Wastewater Treatment Plants." *Water Pollution Control Federation* 52 (1): 76–88.

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

EPA. 2014. "Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Wastewater Treatment." Unite States Environmental Protection Agency.

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

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

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

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

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

“Green Energy Act, 2009, S.O. 2009, C. 12 , Sched. A | Ontario.ca.” 2017. Accessed January 5. http://www.ontario.ca/laws/statute/09g12.

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

Hernández-Sancho, Francesc, and Ramón Sala-Garrido. 2009. “Technical Efficiency and Cost Analysis in Wastewater Treatment Processes: A DEA Approach.” *Desalination* 249 (1). Elsevier B.V.: 230–34. doi:10.1016/j.desal.2009.01.029.

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

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

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

Ontario. 2016. *Ontario Regulation 452/09: Greehnhouse Gas (GHG) Emission Reporting*.

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

Prosser, Monica, Vanessa Speight, and Yves Filion. 2013. “Life-Cycle Energy Analysis of Performance- Versus Age-Based Pipe Replacement Schedules.” *Journal - American Water*

Works Association 105: E721–32. doi:10.5942/jawwa.2013.105.0157.

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

Regional municipality of Waterloo. 2017. "Regional Development Charge."

Rehan, Rashid. 2011. "Sustainable Municipal Water and Wastewater Management Using System Dynamics," 75.

Rehan, Rashid, Mark A. Knight, Andreh J. A. Unger, and Carl T. Haas. 2014. "Financially Sustainable Management Strategies for Urban Wastewater Collection Infrastructure - Development of a System Dynamics Model." *Tunnelling and Underground Space Technology* 39. Elsevier Ltd: 116–29. doi:10.1016/j.tust.2012.12.003.

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

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

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

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

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

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

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

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

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

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

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