A System Dynamics Model for Integrated Water Infrastructure Asset Management

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Abstract

This paper presents the development of a system dynamics model as a decision support tool for the integrated asset management of water distribution and wastewater collection systems. The proposed system dynamics model integrates physical infrastructure with finance and consumer sectors, and enables user rate-setting and planning of integrated water infrastructure operational and capital works over the life-cycle of the infrastructure (10 to 100 year planning horizon). In practice, the proposed decision support tool helps water utilities to evaluate various management strategies for meeting infrastructure service and financial performance indicators, comply with legislations, and make optimized asset management decisions.

Key words: System dynamics modeling, integrated asset management, water distribution network, wastewater collection network.

1. Introduction

In an urban water system, the water distribution infrastructure system provides fresh water for drinking, and the wastewater collection infrastructure system collects the used water which are sent to treatment, and then discharged to streams (Grigg 2012). Ageing and deteriorating water infrastructure systems along with lack of maintenance have accelerated the deterioration of these vital assets. The Water Opportunities and Water Conservation Act 2010 recognizes the requirement of financially sustainable plans for water and wastewater systems. In addition, it requires plans for asset management of physical infrastructure, water conservation, and risk assessment and mitigation (Rehan et al., 2011). Thus, a municipality that seeks to sustain its aging water infrastructure systems with limited financial resources requires an asset management plan. Grigg (2012), EPA (2011), Water Environment Research Foundation (2001), Falls et al. (2001) and TAC (1999) provide a number of definitions and guidelines for asset management. A common theme in most of the definitions is the emphasis on use of limited resources in an efficient and sustainable manner. Grigg (2012) offers a short and useful definition as “Asset management for infrastructure is an information-based process used for life-cycle facility management across organizations”.

Water distribution and wastewater collection systems are placed adjacent to each other, so deterioration in one can affect the physical, financial and social aspects of the other system. Rehan et al. (2013) argue that Ontario’s Ministry of Environment (MOE, 2007) identifies the inter-relationship between water and wastewater infrastructure systems, and encourages municipalities to plan these systems in an integrated approach.

Rehan et al. (2013) indicate that the current asset management models apply either to water distribution or wastewater collection systems. The dynamic behavior of water distribution and wastewater collection systems in an integrated approach has not been adequately studied in the published literature. The amount of wastewater generated depends upon the water consumed, and the design flows for sewage systems are estimated as a function of water demand. Water distribution and wastewater collection systems are placed nearby one another, so deterioration in one can affect physical, financial and social aspects of the other system. A deteriorated water main leakage could be a significant source of infiltration to a nearby sewer. Besides infiltration, the leaking water might cause movement of soil particles around a sewer, resulting in loss of support and consequent damage to the sewer pipes. Exfiltration from a wastewater pipe can contaminate ground water which might be a source of supply for the water distribution system.

According to Grigg (2008) the concepts of integration of water and wastewater infrastructure management systems were introduced as early as 1917. Katko et al. (2010) indicate that the concepts integrating water and wastewater infrastructure are familiar, but the idea as a whole has not been fully embraced. The current research is an attempt to develop an integrated strategic asset management for water distribution and wastewater collection systems.

This paper develops a framework for the integrated strategic asset management of water distribution and wastewater collection systems. The framework explicitly models the feedback mechanisms among various components of the integrated system using the system dynamics (SD) modeling approach and thus provides an opportunity to understand dynamic behavior of the integrated system. The Strategic model is comprised of three sectors: Integrated physical infrastructure, finance, and consumer/public policy (Figure 1). Detailed discussions of each sector are presented in section four of this paper. This research is limited to water distribution and wastewater collection networks. The water and wastewater treatment plants, towers, and reservoirs are outside the scope of this research.

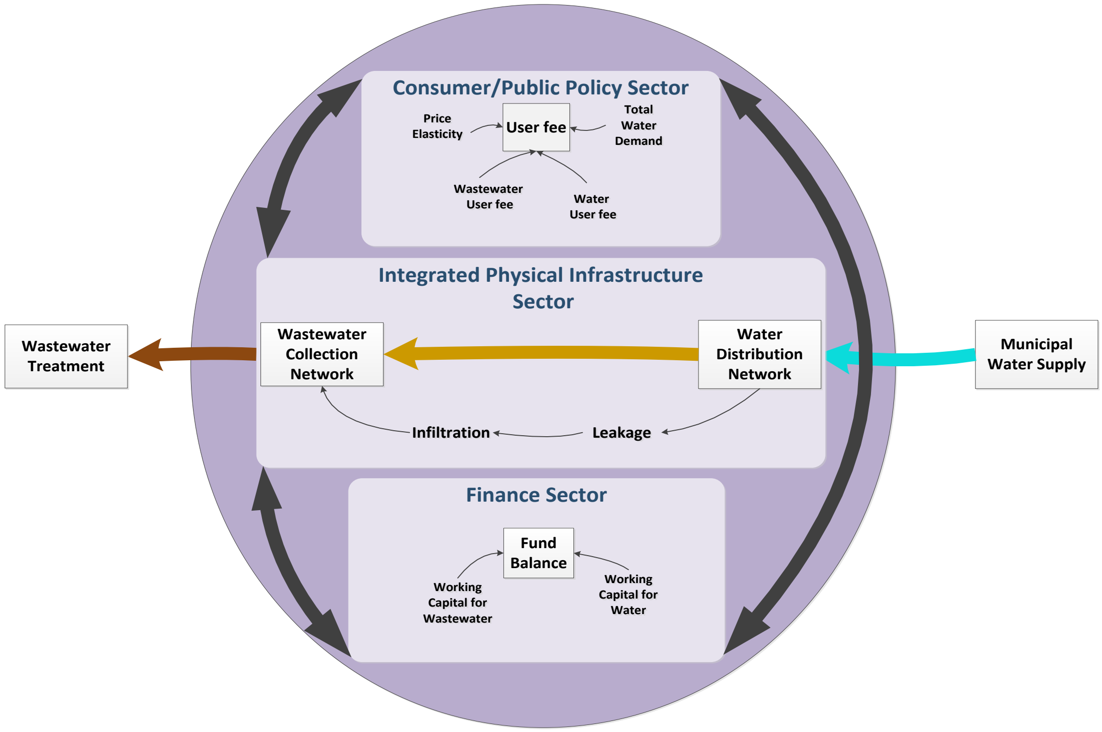

Figure 1: Integrated strategic asset management sectors

2. The Application of SD to Water and Wastewater Infrastructure Asset Management

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

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

Rehan et al. (2013) develop a financially sustainable management strategies model for urban water distribution infrastructure using system dynamics. They present the first known causal loop diagram to lay out the interrelationships among system components of an urban water distribution network. This system dynamics model demonstrates complex interactions and feedback loops among physical, financial, and social/political sectors and is the first known decision support tool to quantitatively simulate the influence of interrelationships and feedback loops in water distribution infrastructure management.

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

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

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

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

A review of the system dynamics models developed for water distribution and wastewater collection networks indicates that the current system dynamics models are applied either to water distribution or wastewater collection systems. The dynamic behavior of water distribution and wastewater collection systems in an integrated approach has not been studied.

3. Causal Loop Diagram Development

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

The amount of total sewage treated depends upon the total sewage generated and infiltration to the sewer pipes (Figure 2). Deterioration in water mains can increase the breakage rate and consequently increase leakage in water mains. A water main leakage could be a significant source of infiltration to a nearby sewer. Besides infiltration, the leaking water might cause movement of soil particles around a sewer, resulting in loss of support and consequent damage to the sewer pipes. Exfiltration from a wastewater pipe can contaminate ground water which might be a source of supply for the water distribution system. Therefore, an increase in water main leakage causes an increase in sewer infiltration. Increased water leakage demands supplying more water to consumers to satisfy their needs. Increased sewer infiltration means more sewage generated and ultimately leads to higher volume of sewage treated (Figure 2).

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

Reinforcing loop R3 shows that an increase in the integrated level of service increases consumers' willingness (acceptance of fee hike) to pay more fees (fee hike). As user fees increase, revenue increases as well, and increased revenue causes increase in the integrated service level (Figure 2, R3).

Balancing loop B1 shows that as the user fee increases, the amount of money that customers pay (user bill) increases as well. This increase leads to a decrease in the satisfaction level. Customer satisfaction is measured quantitatively to determine the satisfactory level of services (on a scale of 0 to 100) delivered to them. As the customer satisfaction level decreases, the willingness to pay decreases, and ultimately user fee decreases as well (Figure 2).

Balancing loops B2 and B3 show increase in total costs of water supply and total costs of sewage decreases available cash for maintenance and rehabilitation, respectively. Shortfall in available cash for maintenance and rehabilitation (capital works) increases the network condition (Figure 2).

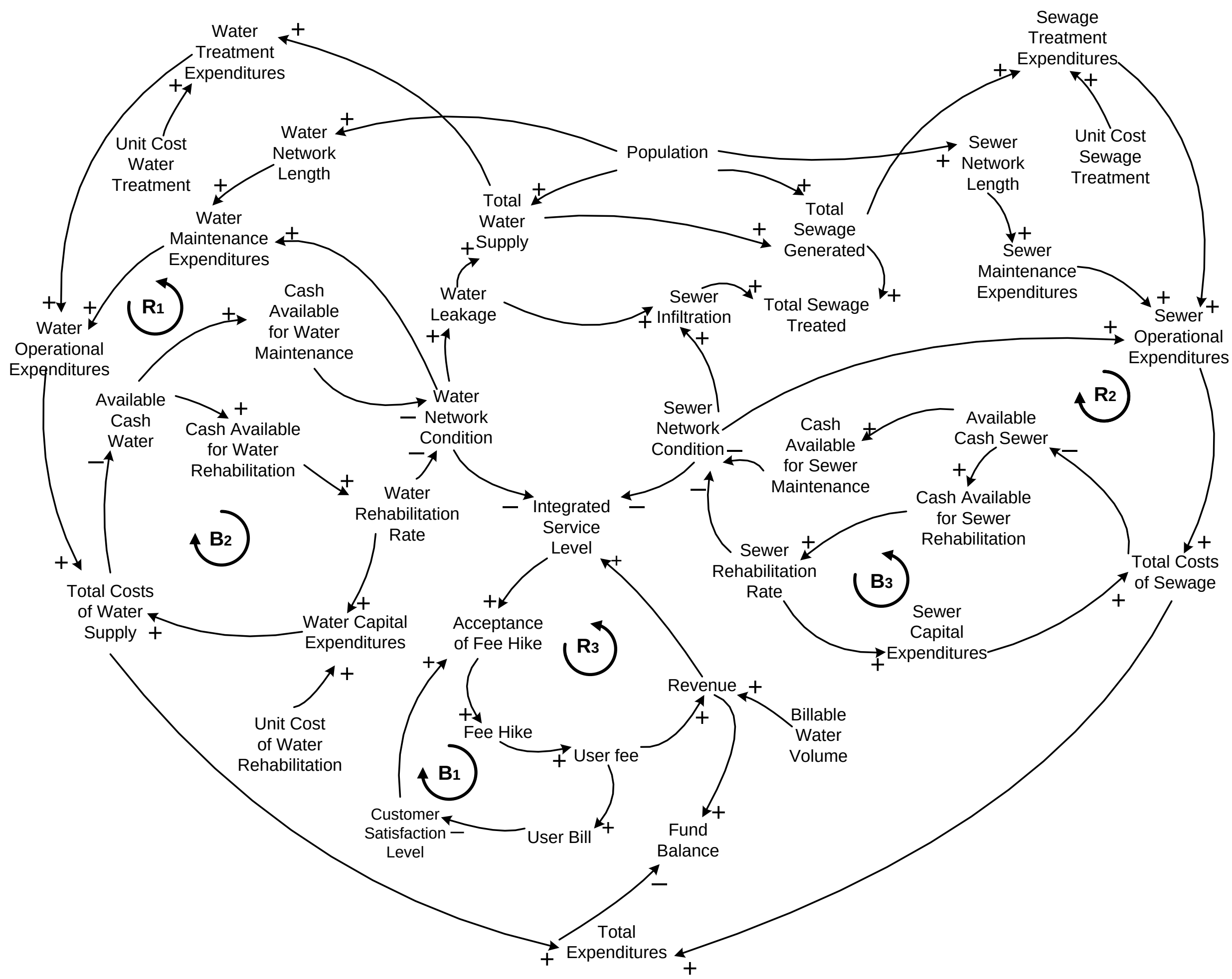

Figure 2: A Causal Loop Diagram for the Integrated Asset Management of Water Distribution and Wastewater Collection Networks

4. System Dynamics Model Development

SD is applied to develop an integrated asset management system for water distribution and wastewater collection networks. The SD demonstration model is used to understand the complex behavior of water and wastewater infrastructure systems, and to show the impact of complex interconnections and feedback loops on management decisions. SD is used for modeling the complexity of integrated water infrastructure systems. If a system is of 4th or greater order then it can be referred to as a high order system where the order refers to the number of state variables (stocks) (Forrester, 1969). In the proposed strategic model, more than four stocks are included within the boundaries of this study model. Examples include the stocks representing inventories of water and wastewater pipes in different condition grades, water demand, user fee, fund balance, etc. Therefore, the study addresses a complex problem which can be modeled using SD. Several commercial softwares are available for SD modeling. The proposed model is implemented using research version 9.1.4 of Stella® software (Richmond,

2001) due to its useful features such as a library of built-in functions, capability of using graphical functions, and sensitivity analysis. Moreover, knowledge of the author and extension to the Rehan et al. (2011; 2013; and 2014) SD models added an important motivation for using Stella® software in the current study. The SD model of this study is comprised of three sectors: (1) integrated physical infrastructure asset, (2) finance, and (3) consumer/public policy. A description of these sectors is presented in the following sections.

4.1 Integrated Physical Infrastructure Asset Sector

This sector represents the asset inventory of water distribution and wastewater collection networks. The physical condition of the water network is classified based upon the age distribution of water pipes (e.g., in 25-year increments). The physical condition of the wastewater networks is divided into five stocks (variables) based upon the internal condition of the pipes using the UK's Water Research Centre rating system proposed in the fourth edition of the Sewerage Rehabilitation Manual (WRc, 2001). Pipes in each stock move about to the next one through an inflow (deterioration modeling). Additional bins are created and added to the model's integrated physical infrastructure sector to extend the inventory of pipes (i.e. incorporate various classes of pipe's material) developed by Rehan et al. (2013 and 2014a). In addition, institutional and commercial flows are incorporated into the calculations of annual total flow. Hence the new flow is computed not only based upon the consumed water and sewage generated from the residential sector, but also including the flow consumed and generated from the institutional and commercial sectors as well (Figure 3).

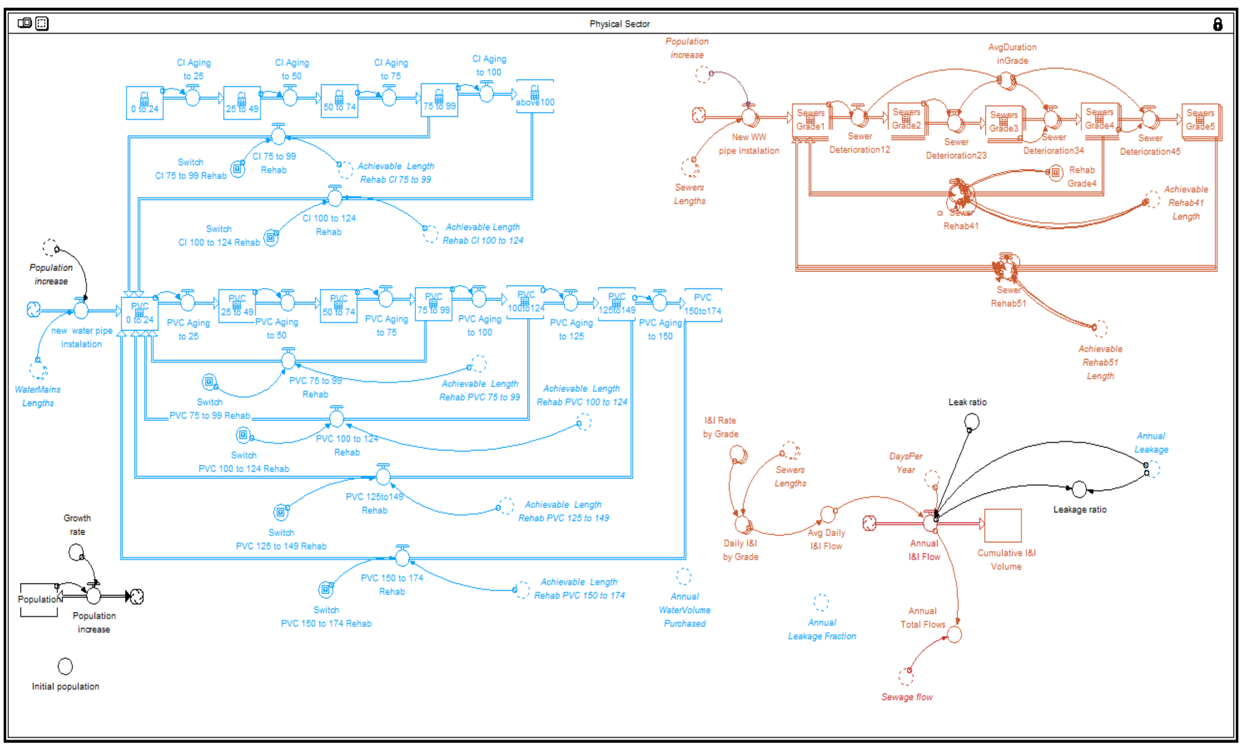

Figure 3: A screenshot of the model integrated physical sector in Stella®.

4.2 Finance Sector

This sector describes the network's financial condition with special emphasis on revenue, expenses, fund balance, debt, and utility user fee. (Figure 4). Revenue is the utility's income that is calculated based upon user fees, total water consumption, and total generated sewage. Fund balance is the difference between the revenue and expenditures of the network in dollars value, and user fees include the unit cost water and sewage ($\$/m^3$) that a utility charges to cover the expenses associated with the water and sewage services. The following extensions are made to the finance sector of the SD model developed by Rehan et al. (2013; 2014a).

4.2.1 Inflation

Rehan et al. (2014b) assume that the unit costs are constant over the simulation period. Thus, the rate of appreciation of costs (inflation rate) is equal to the project depreciation rate needed to discount all costs to the present value. This study incorporates inflation into the finance sector. Therefore, all costs are given as "future value" and various unit costs change over the simulation period.

4.2.2 Service charges

The consumers of a water utility pay for the treatment and collection costs based upon the volume of water consumed and generated (Equation 1). They also need to pay a fixed cost for the services provided to them regardless of the amount of consumed water, which is computed according to the size of service connections (pipe's diameter) (Equation 2). This study incorporates service charges into the calculations of total revenue collected from the consumers. In addition, the annual water consumed by commercial and institutional sectors are incorporated into the total annual water consumption (Equation 3).

$$VC = [(Unit\ Price\ of\ User\ Fee) \times (Annual\ Water\ Consumption_R + Annual\ Water\ Consumption_C + Annual\ Water\ Consumption_I] \quad [1]$$

where TVC is the total variable costs, and R, C and I represent Residential, Commercial and Institutional, respectively.

$$FC = \left[\sum_{d=15cm}^{d=250cm} (Sewage\ Service\ Charges\ Unit\ Price_d\ ) \times (Total\ Length\ of\ Service\ Connction_d)\right] \quad [2]$$

where FC is the total fixed costs and d is the diameter of service connection pipes, *for* d = 15, 19, 25,…,250 cm

The revenue (RV) is computed as the sum of the variable costs (revenue collected from user fees) and fixed costs (service charges).

$$RV = [VC + FC] = \left\{[Unit\ Price\ of\ User\ Fee \times Total\ Annual\ Water\ Consumption] + Switch\ Service\ Charge \times \left[\sum_{d=15cm}^{d=250cm} (Service\ Charges\ Unit\ Price_d\ ) \times (Total\ Length\ of\ Service\ Connction_d)\right]\right\} \quad [3]$$

where total annual water consumption is the sum of the annual water consumption in t residential, commercial and institutional sectors. If switch service charge equal to zero, the revenue is calculated only based on the variable costs; and if it is equal to one, the revenue is the sum of the variable and fixed costs.

4.2.3. Development charges

Developers pay one-time development charges (DC) for the expansion of wastewater collection infrastructure to new customers. Development charges are a source for financing capital expenditures for a water utility. This study incorporates development charges into the finance sector as a source of total income which contributes to fund capital expenditures (Figure 6). Therefore, the new fund balance is calculated as shown in Equation 4.

$$FB = [RV + IE + DC] \qquad [4]$$

where interest earnings (IE) are a source of total income accrued on a water utility's positive fund balance (cash reserves).

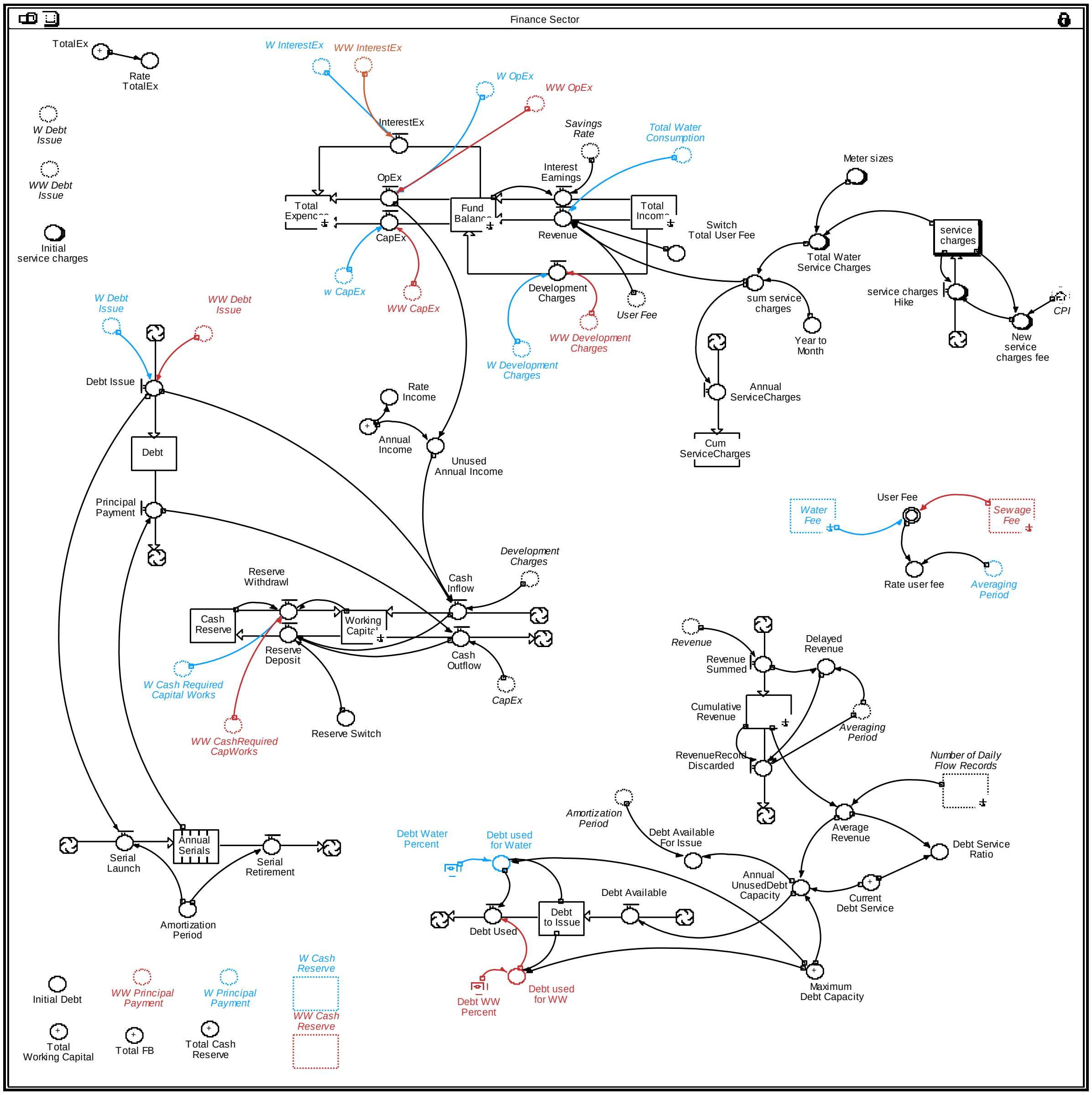

Figure 4: A screenshot of the model finance sector in Stella®.

4.3 Consumer Sector

This sector presents the behavior of consumers in response to user fee oscillations in water demand and level of service (Figure 5). This sector establishes the policy levers and level of service performance (i.e. consumer satisfaction) policies. The following extensions are made to the consumer sector of the SD models developed by Rehan et al. (2013; 2014a).

4.3.1 Price Elasticity of Water Demand

Price elasticity of demand is the percentage change in quantity demanded of a good divided by the corresponding percentage change in price (Lipsey and Chrystal, 1999). Mathematically, price elasticity (η) can be expressed as

$$\eta = \frac{d_q}{d_p} \times \frac{p}{q} \qquad [5]$$

where $\frac{d_q}{d_p}$ is the derivative of demand q with respect to price p at point (p, q) on the demand curve.

The value of price elasticity can range from zero to minus infinity. Depending upon the value that the price elasticity of a good assumes over this range, demand for the good is classified as follows (Lipsey and Chrystal, 1999):

1. *Perfectly elastic:* if $\eta = 0$, whether a price change does not affect the quantity demanded.
2. *Inelastic:* If $-1 < \eta < 0$, then it is implied that the percent change in quantity demanded is less than the percent change in price.
3. *Unitary elastic:* If $\eta = -1$, for every percent increase (or decrease) in price, the quantity decreases (or increases) by the same percentage.
4. *Elastic:* if $\eta < -1$, the percentage change in demand for such a good exceeds the percentage change in price.

Price elasticity of water consumption is influenced by the following factors: price, number, and quality of substitutes available; portion of household income spent on water; price of complementary goods; and length of time considered can influence (Bishop and Weber, 1996). This can also differ based upon classes of consumers (residential, commercial, industrial) and for various seasons. Price elasticity was modeled as a constant parameter in the water distribution and wastewater collection networks SD models developed by Rehan et al. (2013; 2014a). In this study, price elasticity of water demand is considered as a variable parameter based upon classes of consumers (Figure 5).

4.3.2 Affordability

Raftelis (2005) defines affordability as "the ability of customers to pay for utility services billed to them". User rate affordability or user bill burden is typically measured by the annual cost of user bill as a percentage of annual median household income (Equation 6).

A user rate that exceeds an affordability threshold is considered to be unaffordable. The U.S. Environmental Protection Agency reports a range of 2-2.5% as a threshold for the user rate affordability (EPA, 1997). This study adopts a rate of 2% for user rate affordability threshold.

$$Affordability = \left(\frac{User fee}{median\ household\ income} \times 100\right) \qquad [6]$$

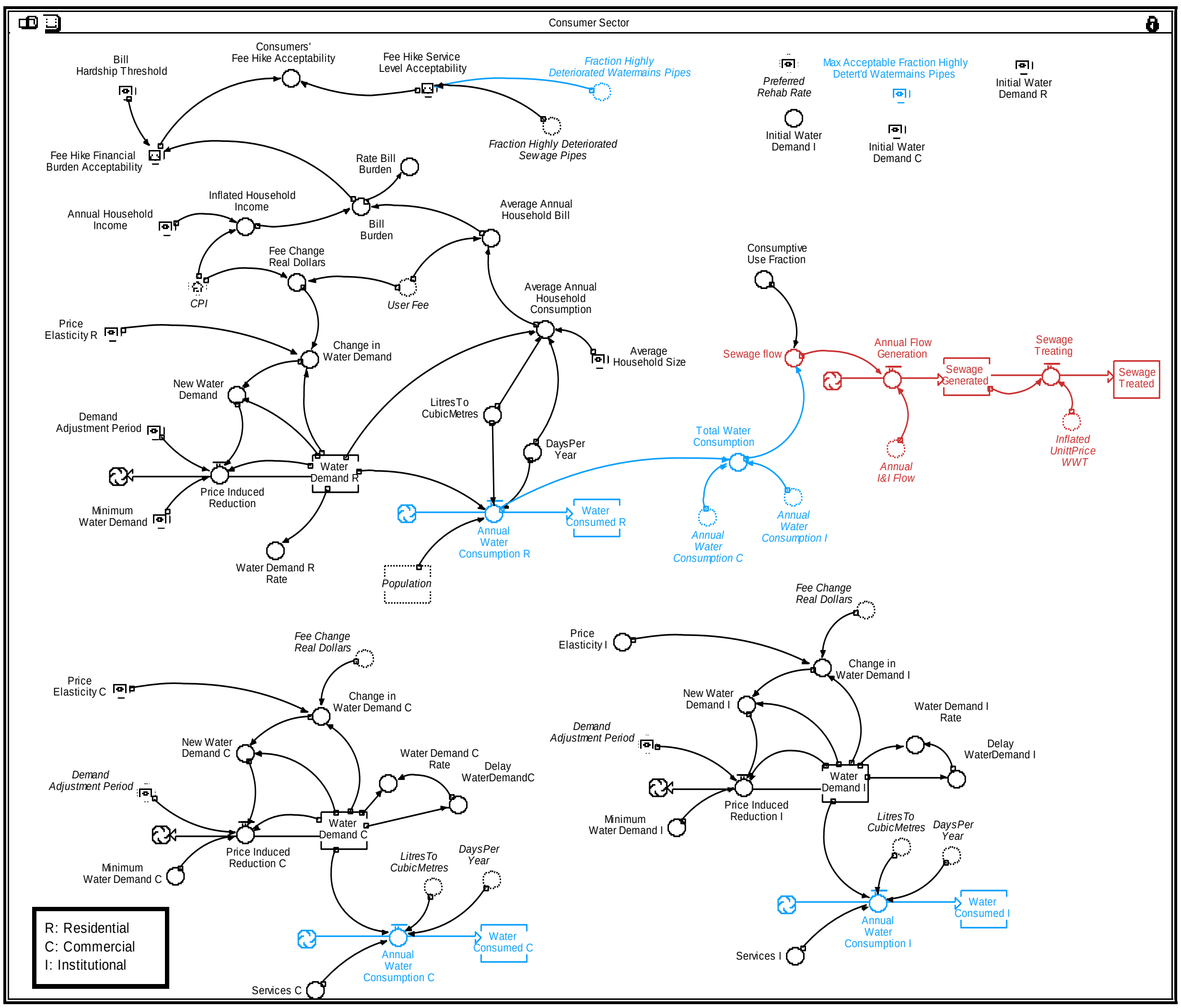

Figure 5: A screenshot of the model consumer/public policy sector in Stella®.

4.4 Model Data Requirements

It is very important that classification and level of detail are appropriate because data collection can be costly and time consuming. To measure the parameters in various sectors of the model, significant data have been collected on critical component/parameters to establish a novel SD tool for the integrated asset management of water distribution and wastewater collection networks. A summary of the required data for the SD modeling follows:

1. Inventory of physical description of water and wastewater infrastructure facilities, including material, age, length and geographical features
2. Usage history (i.e. water demand)
3. User fee and fixed service charges
4. Condition assessment
5. Operating and maintenance history
6. Maintenance intervention criteria, decision criteria, maintenance policy, and unit cost and budget
7. For the purpose of the deterioration modeling of water mains pipes, needed information about breakage history and leakage; and similarly structural grade, and infiltration and inflow for wastewater pipes
8. Rehabilitation, replacement, and renewal costs
9. Price elasticity of water demand

4.5 Model Validation

This section describes specific tests and procedures to validate the proposed SD model, acknowledge the productivity of the proposed SD model, uncover flaws, and enhance confidence in its application. The eight test methods adopted from Sterman (2000) are used to validate the proposed SD model of this paper (see Table 1).

Table 1: Test methods for the SD model validation (adopted from Sterman (2000))

	Test Method	Description	Procedure
1	Boundary adequacy	To assess whether the chosen model boundary is appropriate for the intended purpose	Constructing model boundary charts and presenting them to key experts and review of relevant literature to check if adding plausible structure and changing exogenous variables to endogenous affect the behavior of the proposed model
2	Dimensional consistency	To check the dimensionally consistency of each equation	The Stella® software has the capability to perform dimensional consistency check
3	Structure assessment	To check the level of aggregation for consistency with knowledge of the real system relevant to the purpose	Partial model tests should be conducted to check the rationality of individual decision rules. For example, the level of aggregation for integrated water and wastewater model can be tested by comparing the behavior of water and wastewater models individually to the integrated model
4	Parameter assessment	To ensure that the parameter values are consistent with relevant descriptive and numerical knowledge of the system and variable has a clear meaning	Parameters for which numerical data is available, statistical methods are employed to estimate the parameters. When numerical data is not available for some parameters, then those can be estimated judgmentally using information from interviews, workshops, and archival materials, etc.
5	Extreme condition or reality checks	To check for unlikely behavior of the system in face of extreme conditions	Assigning minimum and maximum values to various parameters
6	Integration error	To ensure that the model results are not sensitive to the choice of time step	Conducting simulations by cutting the time step values in half and test for changes
7	Behavior anomaly	To check if a change or deletion of a relationship has anomalous behavior result	Replacing equilibrium assumptions with disequilibrium structures
8	Sensitivity analysis	To check how model predictions respond when the uncertain parameters are varied over the feasible range of uncertainty	Numerical sensitivity: numerical changes Behavior sensitivity: modes of behavior changes Policy sensitivity: Policy implication changes

5. Conclusions

This paper reviews application of system dynamics to water distribution and wastewater collection networks. A causal loop diagram is developed to lay out the connection points and identify the interacting feedback loops exist between the physical infrastructure with finance and consumer/public policy sectors. The system dynamics modeling is applied to develop a decision support tool for the integrated asset management of water distribution and wastewater collection systems. The proposed model is the first known integrated approach for asset management of the water and wastewater infrastructure systems. The model data requirements and specific tests and procedures to validate the proposed SD model are elaborated. Further work is needed to validate the results of the model through appropriate applications. In practice, the proposed decision support tool should enable water infrastructure stakeholders to evaluate various management strategies and make optimized strategic-level asset management decisions.

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