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Performance Modeling of Wastewater Collection Networks Using Multi-Proactive Renewal Analysis

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Abstract

Traditionally, highly deteriorated wastewater pipes are given priority in capital work activities. To this end, when capital budgets are limited, money is first allocated to replacing sewers in WRC Internal Condition Grade 5 (ICG 5), the worst condition based on WRc coding system, and the remaining budget is then used for the next condition groups such as ICG 4.

This study investigates the effect of partial allocation of capital budgets between fully-deteriorated (ICG 5) and semi-deteriorated (ICG 4) sewers, using a system dynamic modeling approach over the design life of the asset. The results of analyzing a Canadian wastewater collection network show that a multi-proactive rehabilitation strategy can be more effective in the long-term financial planning of wastewater collection networks. Municipalities and utilities can use the decision-support tool provided herein as an effective asset management plan for wastewater collection networks.

INTRODUCTION

The performance of municipal infrastructure assets plays a key role in the prosperity of cities. It is accepted that a strong correlation exists between public health and inhabitants' longevity and the level of service provided by buried linear infrastructures including water supply and wastewater collection networks (NAMS and IPWEA 2011). The Canadian Infrastructure Report Card (2016) estimates the replacement value of wastewater infrastructure to be $234 billion, 70% of which is linear assets. The current average annual rate of reinvestment in wastewater networks, including rehabilitation and new installation works, is 0.7% which causes a decline in the condition of networks over a long period. To maintain the current level of service throughout the assets' service life, the reinvestment rate of 1% to 1.3% is recommended (Félio et al. 2016). However, reaching this investment target is encumbered by limited financial resources of cities (Mirza 2007).

Recent Ontario provincial and Canada federal regulations direct municipalities and water utilities to deliver their services in a financially sustainable manner. In other words, water system expenses must be covered by revenue generated by user fees, without any incorporation of external financial resources. The Sustainable Water and Sewage Systems Act (2002) along with Safe Drinking Water Act (2002) requires all municipalities and public utilities to report financially sustainable plans, including the full cost of services, infrastructure management plans, and cost-recovery reports. Since 2010, according to Water Opportunities and Water Conservation Act (2010), water service providers and municipalities have been mandated to submit annual reports on the current and future physical condition of water and wastewater infrastructure, and publish long-term water and wastewater financial plans to ensure that all future generations demand will be met (MEO 2007). Additionally, the Public Sector Accounting Board (PSAB) statement – PS3150 – issued by the Canadian Institute of Chartered Accountants, requires all public water utilities to report all their tangible assets along with their depreciation in their financial statements. To comply with the regulations, the rate-setting should ensure that the financial sustainability requirements are satisfied and that the same level of service will be maintained for all generations.

The sewage-system expenditures related to operational and capital costs are directly affected by the physical condition of pipes within the system. Therefore, awareness of their structural and operational functionality through quantifying their internal condition requires estimating the relevant current and future expenses. The United Kingdom's Water Research Center (WRc) suggests a grading protocol to categorize pipes into five Internal Condition Grade (ICG) groups, from ICG-1, which represents the best condition (i.e., a completely sound structural condition) to ICG-5, which represents the worst condition (i.e., bordering on an imminent collapse) (WRc 2001). The WRc grading system, or customized version developed by WRc (such as NASSCO's PACP program), is widely used by most water utilities throughout the world, including Canada and the United States.

Dealing with budget allocation is one of the main concerns of decision-makers with limited available budgets. Thus, they need for optimal renewal strategies, for the limited allocated spending, that will provide the best possible network performance over the long-term. The common and rational approach used by decision-support tools has been to eliminate all the worst pipes in wastewater networks first - all ICG-5 pipe segments.

Using a System dynamics (SD) model the hypothesis that dividing the rehabilitation capacity between fully-deteriorated (i.e., ICG-5) and partial-deteriorated (i.e., ICG-4) pipes may result in a better optimum financial and network performance is investigated through the development of a case study built using actual data obtained from a medium-sized city in Southern Ontario, Canada.

RENEWAL PLANNING MODELS AND DECISION SUPPORT SYSTEMS

Various proactive rehabilitation and replacement activity planning models, as well as, computer-aided Decision Support Systems (DSSs) have been developed for both academic and commercial purposes. Their application enables water and wastewater utilities to render a rational decision on renewal strategies in the most effective and cost-efficient way. Most of them are found to be powerful in selecting the best renewal strategies or appropriate rehabilitation techniques; nevertheless, they are analyzing sewer systems either from an operational perspective or with no interaction among financial, physical and consumer-related parameters (Bairaktaris et al. 2007; Halfawy et al. 2008; Leitão et al. 2016; Matthews 2010; Sægrov and Schilling 2002; Shehab-Eldeen and Moselhi 2001; Ugarelli and Di Federico 2010).

Rehan et al. (2011) applied an innovative System Dynamics (SD) modeling approach for financially sustainable management of a aggregated water and wastewater pipes. Taking advantage of Causal Loop Diagrams (CLDs) and SD method, an asset management planning model is developed for setting managerial policies while considering the interrelationships and feedback loops among three main sectors: physical inventory, consumers, and finance.

To identify the complex system behavior and interactions among the sectors, advanced conceptual CLDs are developed to act as a basis of financially sustainable management SD models applied in wastewater collection networks. The model establishes policy levers such as user fees, allowable fee-hike rates, and rehabilitation rates, in a long time frame covering the life cycle of typical sewers (Rehan et al. 2014a). The model is later implemented to a medium-size network of a Southern Ontario city, which serves a population of 120,000. Three different borrowing scenarios are compared to explore the effects of changing two main indicators: the total expenditures which represents the network's financial performance, and the fraction of sewers in the ICG-5 group, which represents the network's service performance (Rehan et al. 2014b). The SD models for both water distribution and wastewater collection networks are advanced and then the two are integrated into an asset management system to investigate their interactive effects (Ganjidoost 2016; Ganjidoost et al. 2017).

In developed wastewater SD models mentioned above, revenue is generated by sewage fees collected from end-users. Sewage fee changes are capped by maximum annual fee-hike rates to ensure consumer affordability. Hence, a lower fee-hike rate is often desired from both a political and consumer perspectives. Lower cap for fee-hike rate means a tighter utlity budget constraint. The optimal fee-hike rate is deemed to be the lowest hike that will achieve financial and network performance requirements or indicators.

PROACTIVE PERFORMANCE MODEL USING SYSTEM DYNAMICS

System Dynamics (SD) Method. SD is a feedback-based, object-oriented modeling paradigm developed by Forrester (1958) to model and understand the non-linear behavior of complex systems. SD modeling involves studying the system as a whole by aggregating information in *Stock* and passing through *Flows* (inflows/outflows) (Forrester et al. 2003). The underlying concept of SD is simulating of how a change in a variable induces a series of perturbations in the system, which is then modified by other variables and by the originating variable. Mathematically, an SD model is founded on the two types of equations: fourth-order Runge-Kutta and first-order Eulerian differential algebraic equations (Shadpour et al. 2015). In this study, an SD model is used as a decision support tool to simulate wastewater long-term performance in terms of financial sustainability and level of service.

Younis and Knight (2010) report a service life of 75 years for concrete sewers. For other pipes (i.e., PVC, AC, VC), the service life of 100 years is assumed (Rehan et al. 2014b). Looking at a 100-year window allows us to prepare more effective financial plans Thus, the wastewater collection network is simulated for a 100-year period using the SD model.

Multi-Proactive Renewal Strategy. The backlog of capital activities along with limited financial resources necessitate making intelligent decisions about budget allocation. The capital budget can be divided between ICG-4 and ICG-5 pipes for renewal actions. The preference ratio of ICG-5 to total deteriorated pipes (R_{pref}) is defined as in the following equation:

$$R_{pref} = \frac{L_{ICG-5}}{L_{ICG-4} + L_{ICG-5}} \quad [1]$$

where L_{ICG-5} and L_{ICG-5} are the total lengths of pipes in the ICG-4 and ICG-5 categories, respectively. Obviously, R_{pref} ranges from 0, where all preference is given to ICG-4 renewal activities, to 1, where all preference is given to ICG-4 renewal activities.

The complex dynamic behavior and interconnection of system components can be graphically explained using Causal Loop Diagram (CLD) tools. These are employed to identify the feedback loops and dynamic causal relationships among system components. Figure 1 shows the CLD related to R_{pref} to demonstrate how a change in R_{pref} affects the performance of wastewater collection systems. The relationship between each two variables is identified by either the positive (+) or negative (−) arrows. That is, if a cause increases, the effects increases above and decreases below what they would otherwise have been, respectively, in positive and negative states (Sterman 2000).

As shown in Figure 1, when the R_{pref} increases, more ICG-5 pipes will be renovated than ICG-4 ones. It means that the elimination rate of ICG-5 pipes is higher compared to ICG-4. Consequently, the network average condition grade will decrease. The less deteriorated network results in lower maintenance cost, due to a reduction in the frequency of pipe cleaning and emergency repairs of collapsed pipes, and less energy consumption, in the case of using pumping stations within the network. Simultaneously, the total volume of Inflow and Infiltration (I&I) into the sewage lines will decline when the pipes are in better conditions, because of fewer expenses incurred due to the treatment of extraneous I&I volumes. Therefore, the operational expenditure and, accordingly, the total network expenditures will decrease. A reduction in total expenditures results in a budget surplus, which appears in a positive fund balance then will be added to the cash available for capital activities. However, the more cash availability for capital activities with a higher priority of ICG-5 depletes the ICG-5 pipe inventory until insufficient pipes remain. Hence, R_{pref} must be decreased to adjust to the current inventory profile. It is shown that the response of an increase in R_{pref} along the feedback loop counteracts the original change and mitigates the original change. This type of feedback loop is classified as balancing loops. Further discussion of other feedback loops with an explanation of the relationships between the components of wastewater collection networks can be found in Rehan et. al. (2014a).

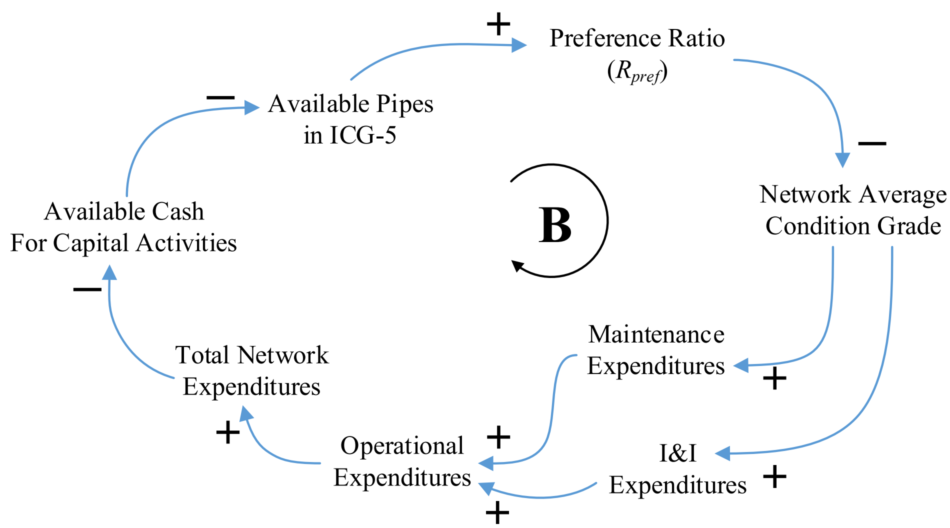

Figure 1. R_{pref} **feedback loop or multi-proactive strategy of wastewater pipeline systems**

Modeling goal and objectives. The goal of the wastewater SD modeling is to obtain a financially self-sustainable system, which its expenses are covered by selling services. To achieve this goal, the following objectives are investigated:

I. Maximize the network's financial performance through minimizing the total expenditures.
II. Maximize the network's service performance through minimizing the network condition grade and the fraction of ICG-5 pipes.
III. Maximize the network's consumer satisfaction through minimizing sewage fees.

Modeling Assumptions. Three main budgeting strategies are assumed to analyze the impact of the preference ratio (R_{pref}) on the budget allocation for renewal activities:

1. A tight budgeting strategy which allows a sewage fee-hike rate up to 7% annually.
2. A normal budgeting strategy which allows a sewage fee-hike up rate to 9% annually.
3. A flexible budgeting strategy which allows a sewage fee-hike up to rate 12% annually.

Table 1 itemized the policy levers for the three main budgeting strategies - Tight, normal and flexible budgets.

Table 1. Modeling policy levers

Policy lever	Tight Budget	Normal Budget	Flexible Budget
Maximum allowable fee-hike rate (% per year)	7	9	12
Maximum acceptable fraction of ICG-5 pipes (% of network)	10	10	10
Desired elimination period of ICG-5 pipes fraction (years)	10	10	10
Preferred rehabilitation rate (% of network per year)	1.3	1.3	1.3

The model runs for R_{pref} values from 0.1, which means 10% of the capital budget is allotted to ICG-5 renewal, to 1, which means 100% of the capital budget is allotted to ICG-5 renewal. A preferred annual rehabilitation rate is also defined for doing capital works which can be neglected if the fraction of ICG-5 pipes goes beyond a specific maximum acceptable fraction. In these circumstances, the extra fraction must be eliminated in a certain period of time, regardless the preferred rehabilitation rate.

CASE STUDY

The sanitary sewer network chosen for this study belongs to a mid-size city located in Southern Ontario. The network serves 83,000 residents by operating a rather large network, 411.6 km long, consisting of various pipe material including Vitrified Clay (VC), concrete (C), polyvinyl chloride (PVC) and asbestos cement (AC). The pipe materials and Internal Condition Grade (ICG) inventory profile of the network are shown in Figure 2. This figure shows that almost half of the pipes are in the sound operational/structural condition (ICG-1) while deteriorated pipes in ICG-4 and ICG-5 comprise 11% and 9% of the network, respectively.

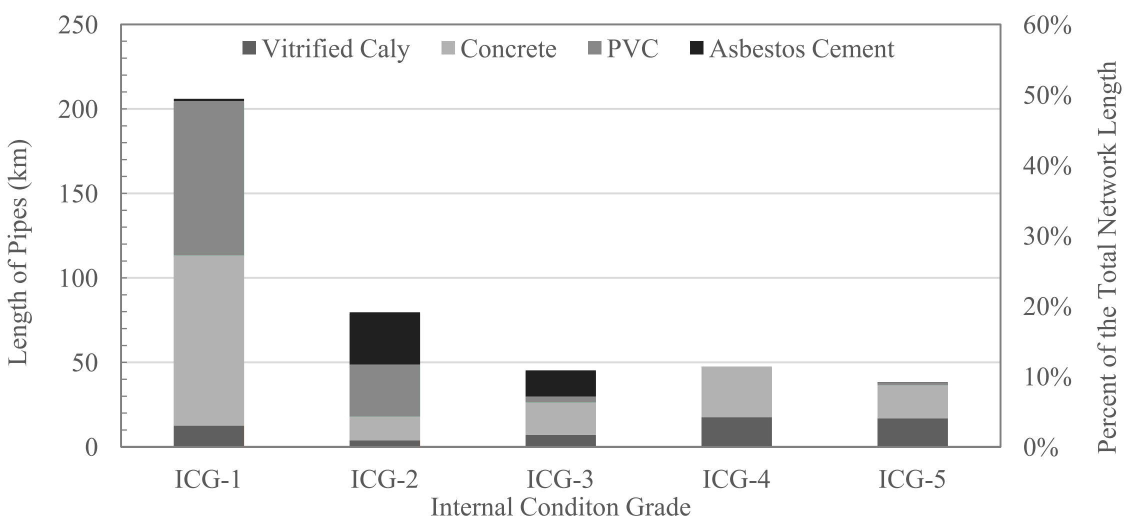

Figure 2. The inventory profile of the case study wastewater collection network

The consumers are charged based on water volumes metered and separately billed for water and wastewater services. The total expenses consist of operational (maintenance and wastewater treatment costs) and capital (rehabilitation and replacement costs). Table 2 tabulates the unit costs collected by Ganjidoost (2016) and used in this study. New pipe installations are completed to address population growth. Since the network expansion is assumed to be funded through an external resource (i.e., development charges), the network length is assumed constant for the 100 year SD model simulations.

Table 2. Adopted unit costs collected by Ganjidoost (2016)

Characteristics	Amount	Unit	Characteristics	Amount	Unit
Operational Unit Costs			Capital Unit Cost		
Maintenance Cost for ICG-1 Pipe	8.56	\$/m	Rehabilitation Unit Cost	600	\$/m
Maintenance Cost for ICG-2 Pipe	9.12	\$/m	Replacement Unit Cost	1000	\$/m
Maintenance Cost for ICG-3 Pipe	9.83	\$/m			
Maintenance Cost for ICG-4 Pipe	10.7	\$/m	Initial Sewage Fee	1	\$/m3
Maintenance Cost for ICG-5 Pipe	11.8	\$/m			
Wastewater treatment cost	0.77	$\$/m^3$			

RESULTS AND DISCUSSION

A number of simulations are performed to evaluate the three budgeting scenarios regarding various R_{pref} values. For this purpose, R_{pref} value is changing from 0.1 to 1 by an increment of 0.1. The results show that a few simulations fail to: (1) meet the financial sustainability requirement and/or; (2) eliminate the maximum acceptable fraction of ICG-5 pipes within the specified five years. It is apparent from Table 3 that if capital budgets are traditionally allocated (i.e., R_{pref} =1) for the tight budget case, the system will not meet the financial or performance requirement.

Table 3. Checking the requirements for SD models acceptance

		Preference Ratio (R_{pref})									
	Requirements	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Tight Budget	(1)	×	×	✓	✓	✓	✓	✓	✓	✓	×
	(2)	×	×	✓	✓	✓	✓	✓	✓	✓	×
Normal Budget	(1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	(2)	×	×	✓	✓	✓	✓	✓	✓	✓	✓
Flexible Budget	(1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	(2)	×	×	✓	✓	✓	✓	✓	✓	✓	✓

Requirements: (1) financial sustainability requirements and (2) eliminate the maximum acceptable fraction of ICG-5 pipes in five years.
✓: meet the requirement, ×: fail to meet the requirement.

Figure 3 provides the results of cumulative total expenditure obtained for each scenario that met both requirements. This figure shows that the wastewater collection network has the best performance when R_{pref}=0.6 for all three budget conditions. A small discrepancy between the plots associated with normal and flexible budgeting scenarios shows the fact that the extra money doesn't enhance the network performance for this case study. Therefore, the higher allowable fee-hike rate is not helpful to improve the financial performance of the system.

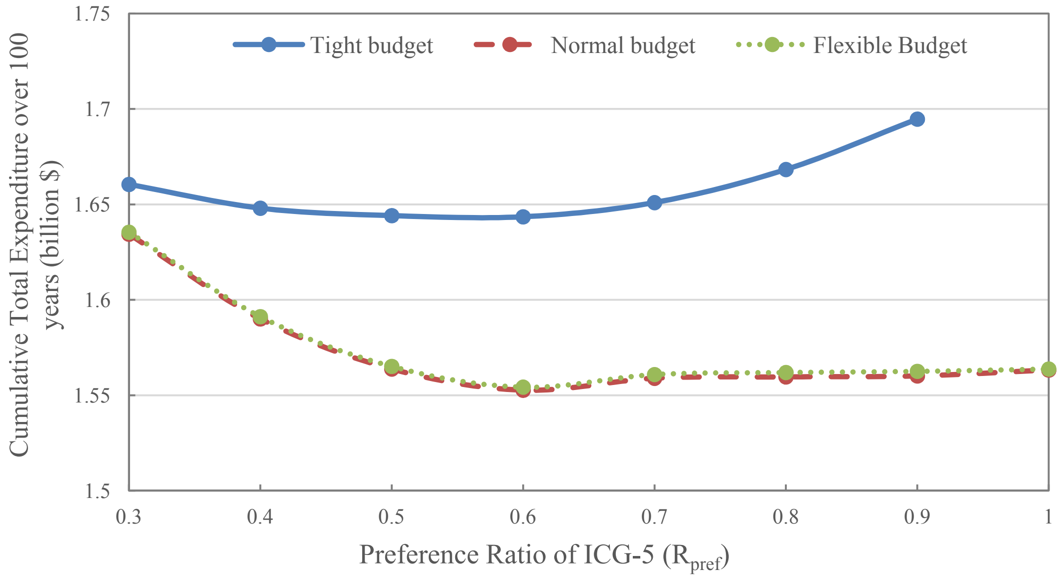

Figure 3. Simulation results of total expenditures

The percentages of highly deteriorated pipes (ICG-5) for each simulation are illustrated in Figure 4. The 100-year average and final measures of this variable are depicted in Figure 4(a) andFigure **4**(b), respectively. Although a noticeable difference is found between scenario 1 and two other scenarios, the ultimate fractions of ICG-5 pipes at the end of the simulation period are almost the same for all three ones, especially for R_{pref} greater than 0.5. From the ICG-5 fraction point of view, the value of 0.6 as a preference ratio (R_{pref}) results in the best service performance, except for scenario 1 and 2 in respect of the 100-year average of ICG-5 fraction. Similar behavior is also shown in the figures related to the average network grade (Figure 5a and 5b).

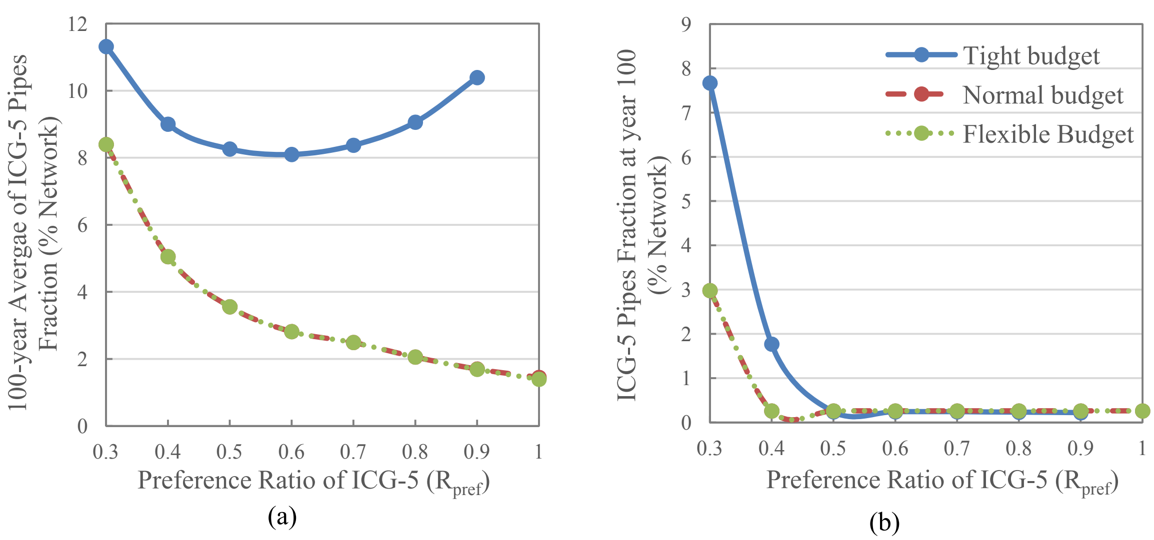

Figure 4. Simulation results of ICG-5 pipes fraction