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DECISION SUPPORT FRAMEWORK FOR URBAN STORM WATER DRAINAGE INFRASTRUCTURES MANAGEMENT: COUPLED GIS AND SYSTEM DYNAMICS MODEL

Abebe, Yekenalem, MSc[1, 2], Tesfamariam, Solomon, PhD[1]
[1] School of Engineering
University of British Columbia (UBC)
3333 University Way, Kelowna, BC, Canada, V1V1V7.
[2] yekenalem.abebe@ubc.ca

Abstract: Storm water drainage infrastructures are composed of multiple subsystems that are geographically distributed and interdependent. All system components are expected to function based on their intended design capacity over the planning horizon. However, this is not the case due to environmental, physical and operational factors affecting their performance. Therefore, to maintain the required level of service, effective asset management system is crucial. This research tries to address the problem by proposing a holistic management approach using system dynamics and GIS applications. The proposed framework brings a single, unified way of investigating all asset components and their interaction in the management process. Furthermore, it can provide the platform to consider both space and time in the decision-making process. The framework is divided into three modules: the first module deals with the sewer network (pipes, manholes, and inlets/outfalls), the second module is for LID technologies (storage, infiltration, and filtration), and the last module deals with open channel flow routes (gutters, culverts, and ditches). The proposed framework is discussed in detail and a sample model for a storm water pipe network is presented. The model can be used to evaluate the current and future condition of asset components and plan appropriate interventions to improve the overall performance of the system. Furthermore, each management activity can be associated with a cost function to estimate the total life-cycle cost of the system.

Keywords: asset management, urban drainage, storm water, life cycle cost, system dynamics, GIS

1 Background

The storm water drainage infrastructures are the first line of defense from pluvial flooding and play a key role in protecting the environment. At present, infrastructure deterioration, increasing service demand, and climate change (CC) are the main planning challenges for the sector. According to Statistics Canada (2015), the Canadian population, considering the high-growth scenario, is expected to reach 63.5 million over the next 50 years. This population growth will concentrate in urban areas, which requires new infrastructure development and alteration in land cover towards predominantly impervious surfaces. Such shifts will reduce the amount of water that infiltrates and can intensify runoff rate (Pauleit et al. 2005; Harbor 1994). Furthermore, due to climate change, heavy precipitation events are expected to increase in frequency and intensity (Pachauri et al. 2015). In Canada, over the last century, annual precipitation increased by 13% in the south and annual snowfall increased up to 20% in the north (Groisman & Easterling 1993). Changes in precipitation patterns towards more intense storms could further aggravate pluvial flooding. To worsen the problem, in 2016, more than $10 billion worth of storm water assets was in poor or very poor condition across Canada, and with the current reinvestment level, a further decline in asset condition is expected (Canadian Infrastructure Report Card 2016). The amount of capital required for asset rehabilitation and expansion programmes can further increase over the coming decades due to the synergic effects of infrastructure aging, urbanization and climate change (Rajani and Kleiner 2001; Carter et al. 2015). Consequently, cities must plan and execute well-planned public works to upgrade and maintain their level of service to support a resilient community. Tackling the issues require a holistic and coordinated infrastructure management approach involving different disciplines and departments.

Infrastructure management provides a structured approach to the construction, use, and decommissioning of infrastructure assets to optimize service delivery and minimize life-cycle costs (Flintsch and Bryant 2009). Storm water drainage infrastructures are costly to construct and would be even more expensive to replace. Therefore, high priority must be given to maintaining the physical integrity of the assets and preserve the hydraulic capacity of the system. However, due to inadequate focus on operations and maintenance, many utilities practice reactive maintenance (Grigg 2012). Therefore, most of the operational expenditure is associated with emergency response and replacement of failed components. While assets that have not failed will continue to deteriorate and undiscovered defects get worse, compounding the problem for the next years to come. Lack of preventive maintenance usually results in a faster decline in condition, which requires a higher replacement and emergency response costs. Infrastructure management process involves multiple stockholders including policymakers, politicians, engineers, accountant and other disciplines and the community in general. The decision-making process must consider a wide range of conflicting variables that have both short-term and strategic implications. Furthermore, these assets are geographically distributed, and their performance is strongly related to the local environmental and operational conditions.

System dynamics (SD) has been intensively used to model various engineering problems and it has been one of the popular methods for modeling water resource systems. It enables modelers to incorporate results from hydraulic and hydrologic studies with other aspects of a system such as socio-economic development (Beall et al., 2011). Winz et al. (2009) reviewed the theoretical and practical evolution of SD in water resource management and concluded that it provides a suitable framework to address critical issues in the area. Qi and Chang (2011) used SD for water demand estimation that takes into account the interactions among economic and social parameters. Stave (2003) proposed SD to support water management decision making and to facilitate public understanding of various management alternatives in Las Vegas, Nevada. Willuweit and O'Sullivan (2013) proposed a decision support tool for sustainable planning of water supply systems considering urban water balance, climate change, and urbanization. Osman and Hassan (2012) used SD to model the relationship between infrastructure systems, operators, customers, and politicians. Ganjidoost et al. (2015) proposed a system SD for integrated urban water infrastructure management. Rehan et al. (2014b) also demonstrate the implementation of a similar model for managing wastewater collection systems.

However, most of the previously reported models provide a generalized representation of asset components in the model, regardless of their geographic location. For example, Ganjidoost et al. (2015) assumed uniform deterioration rate for all metallic pipes in the network without considering the local factors that can affect the deterioration process. Detail considerations regarding the local condition that influences the operation and maintenance requirements of an individual asset are important to have a robust decision support tool. Therefore, to remedy SD model limitations and incorporate spatial dimension in the analysis, a coupled GIS and SD model is proposed, which can provide the platform to consider both space and time in the decision-making process. The proposed methodology is discussed in detail in the next section. Section three and four present the case study and conclusion respectively.

2 Methodology

SD models are built to understand/solve a particular problem and it provides a methodical approach to policy analysis (Stave 2003). SD can be used to study any complex system that exhibits interdependence, mutual interactions, information feedback, and circular causality (Pejić-Bach & Čerić 2007). Complex systems can arise from a large number of factors that must be considered in making a decision or due to a counterintuitive interaction between system components. SD allows us to investigate how systems evolve over time and it can easily be extended to included additional problems as they arise.

SD involves both qualitative and quantitative modeling approach. Qualitative modeling like causal loop diagrams improves our conceptual system understanding while quantitative modeling helps us to investigate and visualize resource levels in the system. The first step in SD modeling is system conceptualization to layout the system structure and critical relationships among variables (Pejić-Bach & Čerić 2007). These relationships are defined by identifying feedback loops, system archetypes, and delays that exist between objects within the system. In feedback loops, an alteration in one variable impacts other connected variables in the system that in turn affects the initial variable. Recognizing all these connections properly and explicitly is the first step to understanding complex systems. In the model formulation phase, the various pieces of the model are built starting with a simple core model and incorporating more components gradually. It is recommended, in each step, to simulate and test different extreme conditions to check the consistency and stability of the model. Finally, prior to deploying the model for real-world applications, it has to be iteratively verified and validated.

While SD modeling approaches provide the perfect platform to represent temporal processes, they cannot adequately represent spatial processes. For instance, SD models can be used for analysis of different climate change adaptation policies and estimation of cost saving due to adaptation measures over time. However, such models provide no easy way to map these in space. In order to consider the spatial aspects in the modeling process, GIS applications can be used. Given the strength of GIS applications in representing spatial processes with limited temporal modeling capabilities, integrated SD and GIS modeling can be used to study spatiotemporal systems. Various proposed methods tried to add spatial dimensions to SD models. However, the majority failed to provide an explicit relationship between time and space. Furthermore, they can limit the interactive power of SD that constraints modelers form making changes during simulation. To remedy the shortcomings, Ahmad & Simonovic (2001) proposed a spatial system dynamics (SSD) approach, which enables a dynamic data exchange between SD and GIS.

SSD approach provides a two-way exchange of data and information between SD and GIS. This will enable the modeller to have real-time feedback in time and space. The process starts with GIS spatial analysis and transmitting spatial information to the SD model. Next, changes in spatial features with respect to time is analyzed in the SD model and the results are communicated back to GIS. These changes in space subsequently impact decisions/policies in time. Such methods have been widely implemented to simulate diffusion processes like land use/land cover changes and disaster management studies (Liu & Deng 2010; Neuwirth et al. 2015). Figure 1 shows the methodology workflow for the proposed SSD model for drainage asset management.

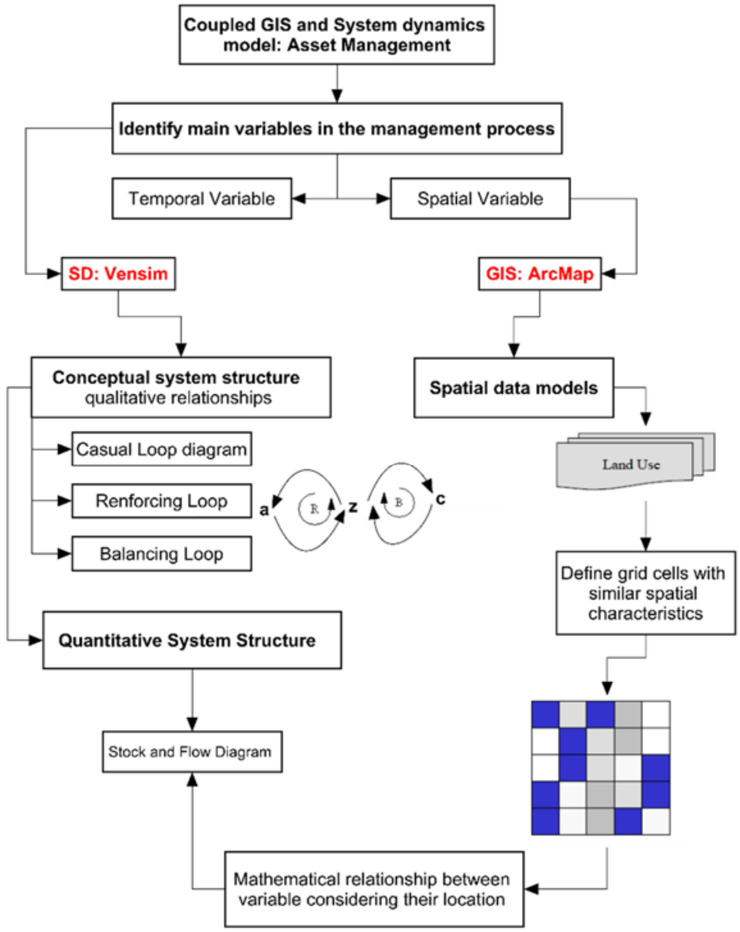

Figure 1: Framework for GIS and System Dynamics Asset Management Model

2.1 SSD Model for Storm water Infrastructure Management

Municipalities are responsible for managing storm water drainage systems that have multiple interdependent subsystems that are geographically distributed. Storm water drainage infrastructures can be grouped into the minor system and the major system. The minor drainage system is designed to handle storms that are more frequent, which includes storm sewers, roadside gutters, and ditches, small channels and swales. Whereas, the major system is intended for the less frequent storm and it consists of natural waterways, temporary overload relief swales, roads and green areas. The major and minor systems are closely interrelated, and their design and management need to be done in conjunction to achieve the overall storm water management objective. In this study, we have grouped the storm water drainage infrastructures into the underground storm sewer, Best Management Practices (BMPs) and other open channel flow routes (Figure 2).

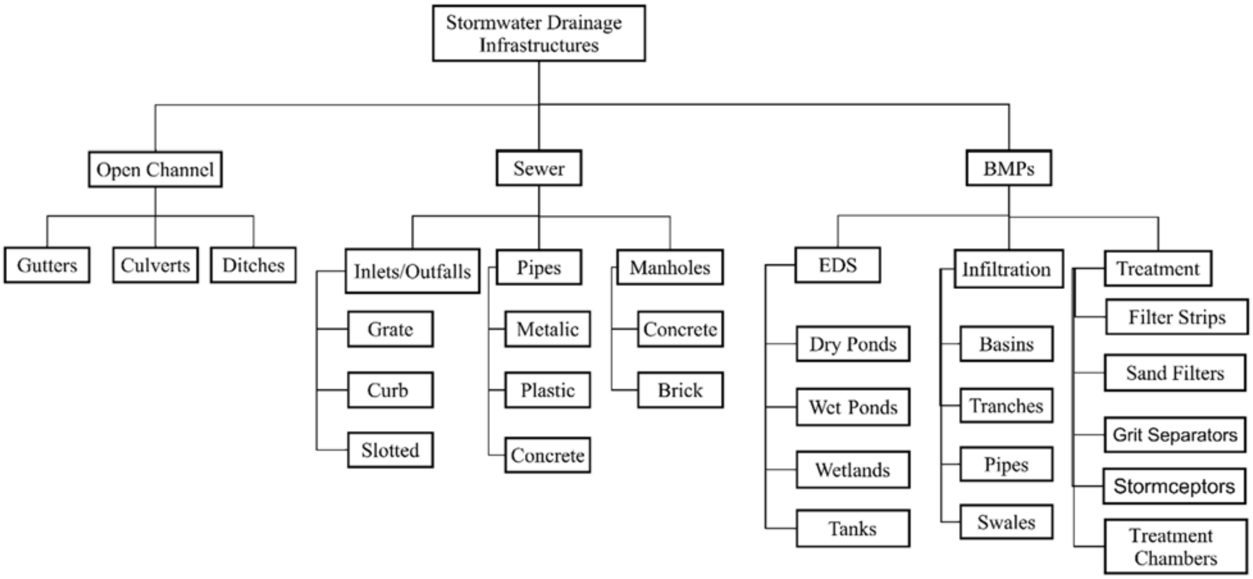

Figure 2: Storm water drainage infrastructures

The main components of a storm sewer are the pipe networks, manholes, and inlet and outfall structures. BMPs help reduces the negative impacts of storm water runoff in urban areas. They can mitigate the impact of urban development and subsequent increase in impervious area by providing runoff storage and facilitating infiltration. A number BMP measures can be deployed depending on the characteristics of the catchment and water quality requirements. The ASCE National Storm water database identifies six major categories of BMPs: ponds, wetlands, vegetative bio-filters, infiltration practices, sand and organic filters and other technology options. All this drainage system components are expected to function based on their intended design capacity over the planning horizon. However, this is not the case due to environmental, physical and operational factors affecting their performance. The various components of the drainage system present a unique operational challenge and require tailored management approach. Even similar asset groups with varied geographic location can have different factors driving the management needs. Managing these types of networked infrastructures require a holistic approach that can assess individual asset as well as the overall system performance.

The proposed drainage asset management model is divided into three main modules and several submodules. The first module deals with the sewer network (pipes, manholes, and inlets/outfalls), the second module is for LID technologies (storage, infiltration, and filtration), and the last module deals with open channel flow routes (gutters, culverts, and ditches). For each module important factors that influence the performance of the system is identified and the deterioration/performance reduction rate is determined. Deterioration rate doesn't depend only on the asset type but also on the geographic location that controls the environmental and operational factors. The performance of each component is graded and aggregated together with other assets in the network to reflect the overall performance of the system (Figure 3). Individual asset performance is measured using two criteria. First, by comparing current hydraulic capacity in relation to design/intended hydraulic capacity. Second, by the asset condition rating. Some BMP treatment facilities can have additional performance attribute considering storm water quality treatment efficiency. The overall system performance is determined by combining the individual assets performance. The model can be used to evaluate the current and future condition of asset components and plan appropriate interventions to improve the overall performance of the system. Furthermore, each management activity is associated with a cost function that is aggregated to estimate the total life-cycle cost of the system.

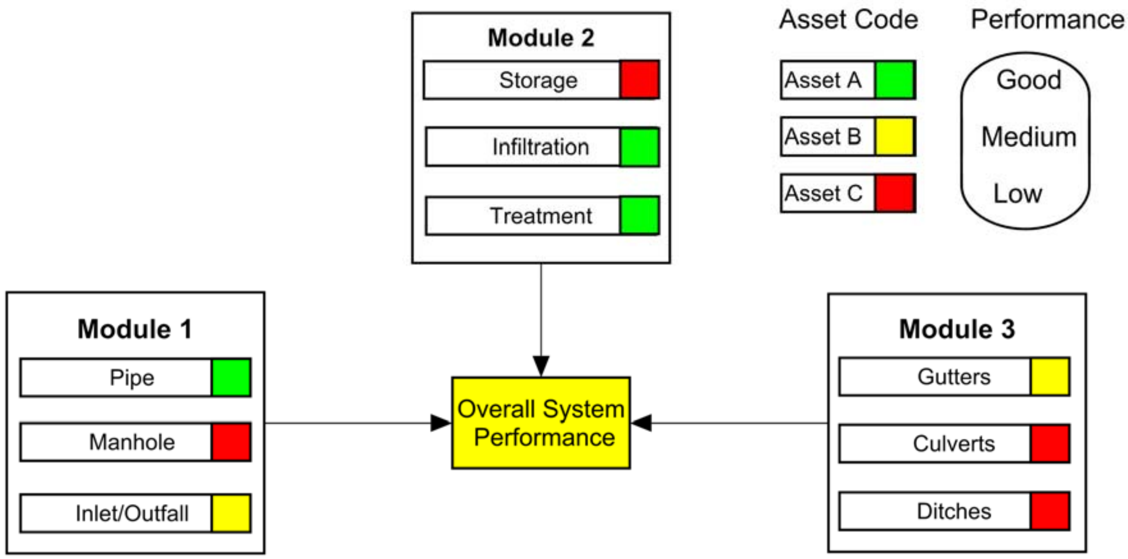

Figure 3: Sample asset management module for storm water asset management

3 Case study

The city of Vernon is located in the Thompson Okanagan region of British Columbia, Canada. It has a total population of around 40 thousand and an area of 95 sq. km. Development is mainly concentrated in the city center and along the Okanagan lake coastlines. The storm water infrastructure is composed of 3979 storm mains with a total length of around 200 kilometers and 7414 service lines. The oldest pipes in the network are asbestos cement and concrete pipes installed in the 1950's. Most of the storm network was constructed after the 1970's and the average age of the pipes in the network is around 16 years. While the recently installed pipes are PVC, the network is mainly made up of metallic pipes. Other main assets in the network include 3270 manholes, 5041 catch basins, 57 dry wells, 101 inlets and 210 outlet structures. A sample module for the storm sewer pipe network is shown in Figure 6. To set up the SD module, first, the initial length of pipes in different condition state must be determined. The important factors that influence the deterioration of pipes are identified and based on these factors the deterioration rate of each pipe is estimated. For example, in the case study area, soil corrosively is one important factor that controls the deterioration rate of pipes. Based on data collected from the municipality, the soil corrosivity is classified into five classes (Figure 4b). Thus, depending on the location of the metallic pipes in relation to the soil type, the appropriate deterioration curves can be assigned.

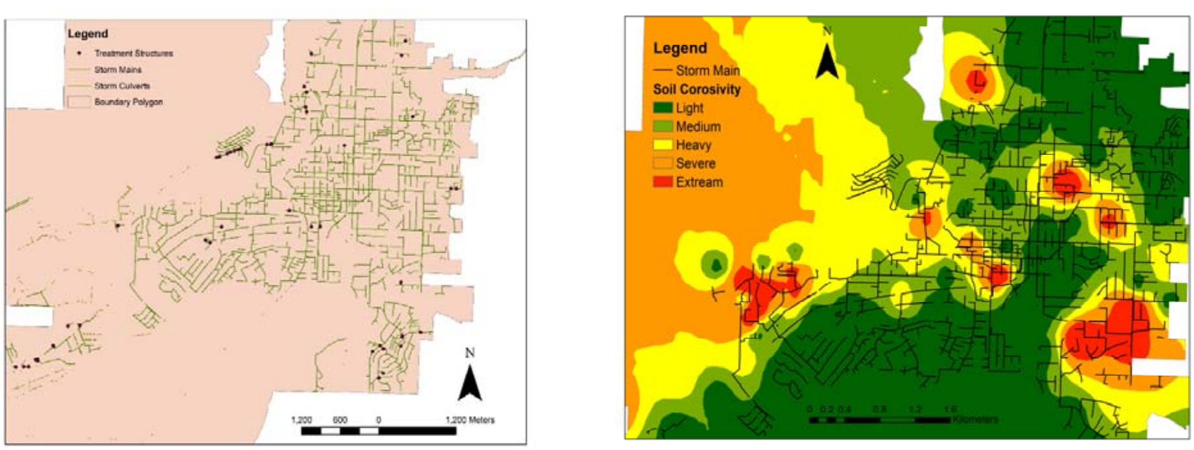

Figure 4: a) Vernon storm water infrastructure and b) soil corrosively map

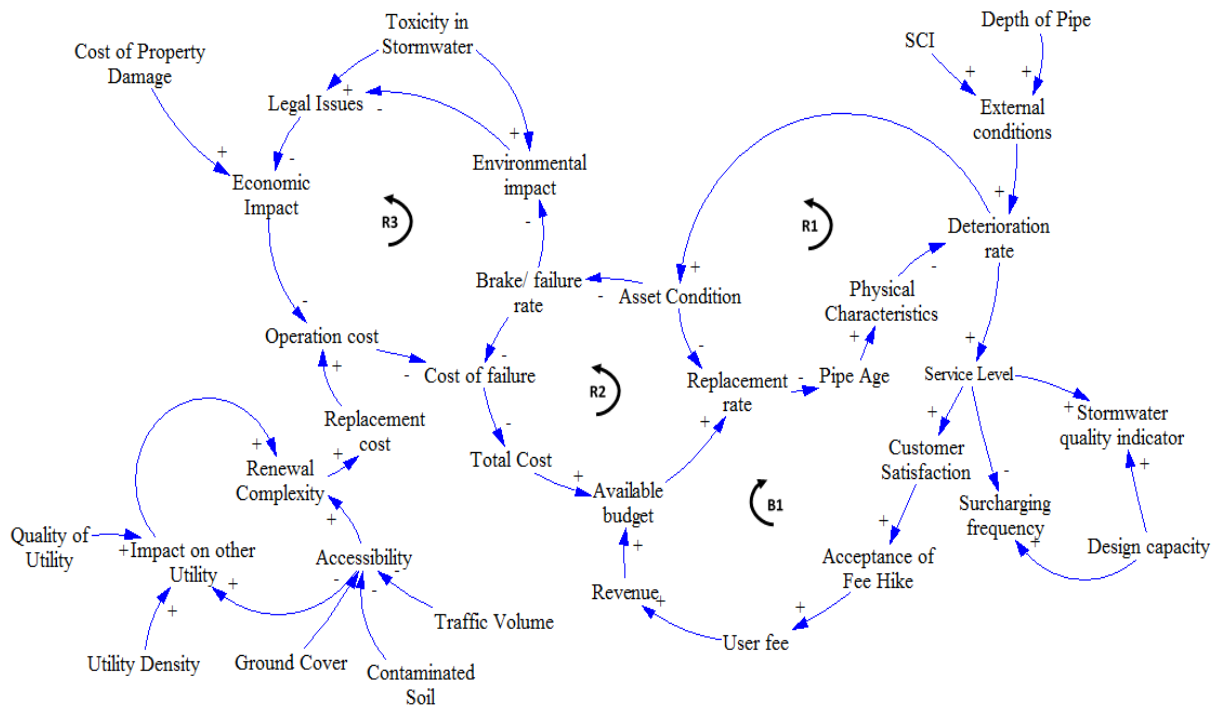

Figure 5: Casual loop diagram for storm sewer management

The qualitative relationships among the various parameters influencing the asset management decision for a storm water pipe network are represented using a Causal Loop Diagram in Figure 5. The balancing and reinforcing loops are the two foundational structures of systems thinking. Reinforcing loop compounds change in one direction, which happens when an action produces a result that influences more of the same action in the same direction leading to exponential growth or collapse. On the other hand, balancing loops help stabilize the system and bring it to the desired state. To achieve this objective the balancing process executes a given action that tries to shift the current state to the desired state (Kim & Anderson 1998). In our case, we have identified three reinforcing loops and one balancing loop. Reinforcement loop one (R1) shows the relationship between infrastructure aging, deterioration rate and asset condition, which in turn raises the requirement for infrastructure renewal and rehabilitation works. R2 shows that declining asset conditions will result in an increase in pipe break rate that will rise the total cost of operating the system and necessitate an increase in management budget. R3 shows the relationship between break rate and possible environmental impact and its monetary implications to remedy the adverse impacts. Balancing loop one (B1) shown that to increase revenue that can be used to maintain the system, increased service level, and customer satisfaction are important factors that influence the acceptability of fee hikes.

Two main stocks are identified in the asset management model: the condition of the pipe network and the total available budget for operation and maintenance (O&M) expenditure (Figure 6). The pipe can be in any one of the five condition states: very good, good, fair, very poor or poor. Different methods are available to determine the condition state of the pipes, including NASSCO grading system or other proposed approaches (ex. Geem et al. 2007; Marlow and Burn 2008; Mehdi S. Zarghamee et al. 2012; Rajani et al. 2006; Rogers et al. 2012). The transition from a given condition to a lower condition state depends on the deterioration rate of the asset, which in turn is controlled by the environmental condition that determines corrosion rate. A simple straight line deterioration or a more robust model (ex. Kleiner et al. 2006; Micevski et al. 2002; Najjaran et al. 2004; Najafi & Kulandaivel 2005; Kleiner & Rajani 2001; St. Clair & Sinha 2012) can be used to represent the deterioration process. Assets are assumed to be replaced when they reach poor or very poor condition. The replacement rate regulates the overall condition state of the pipe network. The two source of income for the operator is revenue collected from users and government subsidies (Figure 6). The break rate in the network, which is one of the controlling factors for the O&M cost, is a function of the condition of pipes in the network. The expected brake rate increases as the condition of the pipe deteriorate.

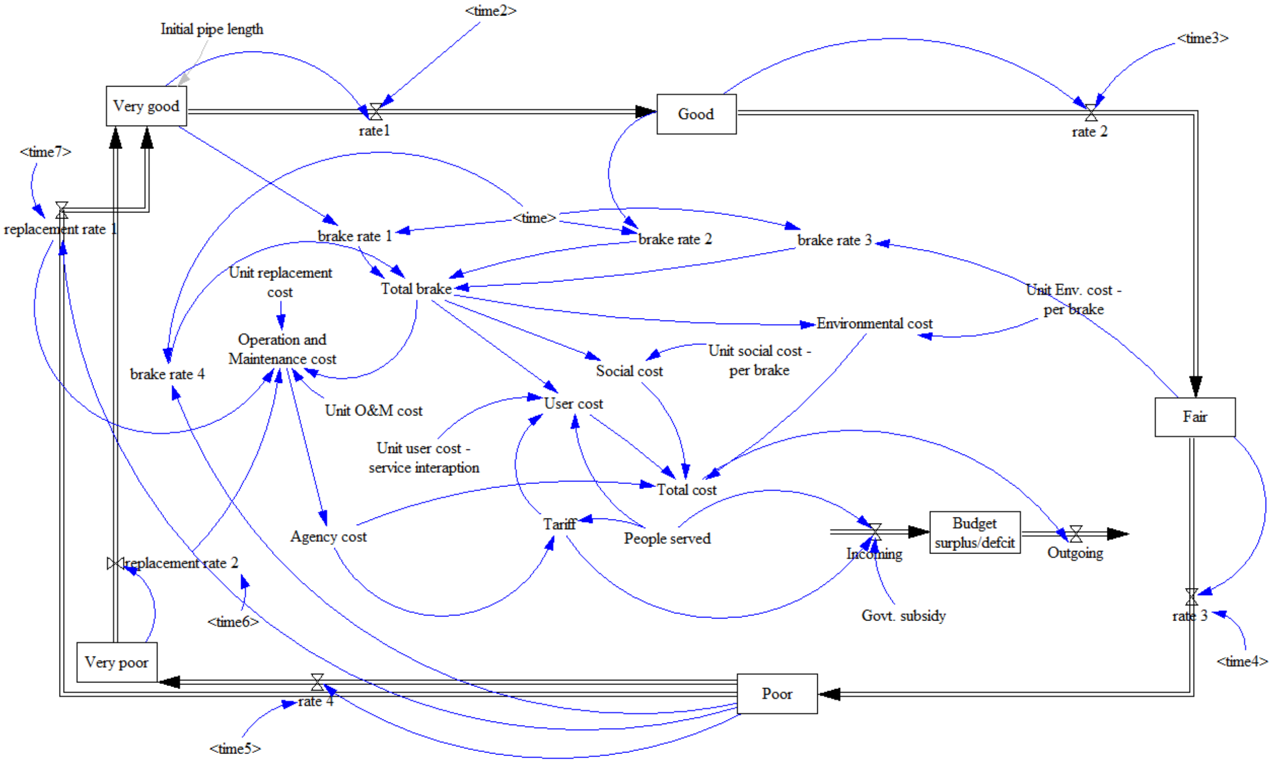

Figure 6: Sample asset management module for storm water pipe network

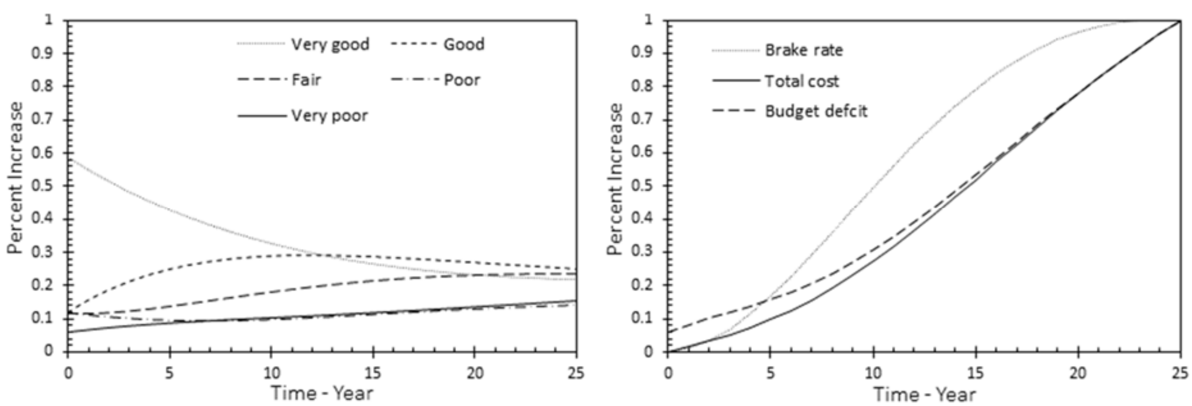

Figure 7: Sample results assuming only 6 percent annual replacement rate of pipes in 'very poor' and 'poor' condition a) Storm sewer pipe condition b) operation and budget deficit increase

The coupling of GIS in the module is essential in modeling spatially variable factors. For example, for determining the failure consequence of a given pipe, the sensitivity of the areas in near proximity to the failed pipe needs to be considered. The deterioration rate and pipe condition state can be used to estimate the expected number of annual pipe brake rate in the network, which directly influences the operation and maintenance cost. Furthermore, decision variables that can be controlled by the municipality, like annual replacement rate and service charge can be included in the module to understand the overall management budget constraints. Figure 6 shows a sample result for a management strategy where 6 percent of pipes in very poor and poor conditions are replaced annually. Assuming more than 70 percent of the pipes are in either very good or good condition at year 1, this strategy might lead to an overall system deterioration. At year 25, around 20 percent of the pipes will be in very good condition. In the same period, the length of pipes in the system with a very poor condition will more than double from 6 to 15 present. Similarly, pipes in fair condition will increase to 24 percent. This, on the other hand, will lead to an increase in the annual pipe break rate, which increases the annual operation cost for the network. The next step of the research project will focus on iteratively optimizing different management strategies and validating the result based on O&M data collected from the

4 Conclusion

Municipalities are responsible for managing storm water drainage systems with multiple interdependent components that are geographically distributed. All these assets are expected to function based on their intended design capacity over the planning horizon. However, this is not the case due to environmental, physical and operational factors affecting their performance. To maintain the required level of service, effective asset management system is crucial. Therefore, a coupled GIS and SD asset management model is proposed, which can provide the platform for considering both space and time in the decision-making process. The proposed GIS and system dynamics model brings a single, unifying framework to investigate all asset components and their interaction in the management process. The model can be used to evaluate the current and future condition of asset components and plan appropriate interventions to improve the overall performance of the system. This paper presented a sample model and the methodological framework for the proposed approach. Detail model development to verify and validate the different modules in the model is still in progress. After the model development is complete it can be used to support municipalities make an informed decision and simulate different management strategies. Furthermore, each management activity is associated with a cost function that can be aggregated to estimate the total life-cycle cost of the system. This is important for storm water service tariff studies and budget allocation.

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