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

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ABSTRACT

Recently enacted regulations in Canada and elsewhere require water utilities to be financially self-sustaining over the long-term. This implies full cost recovery for providing water and wastewater services to users. This study proposes a new approach to help water utilities plan to meet the requirements of the new regulations. A causal loop diagram is developed for a financially self-sustaining water utility which frames water and wastewater network management as a complex system with multiple interconnections and feedback loops. The novel System Dynamics approach is used to develop a demonstration model for water and wastewater network management. This is the first known application of System Dynamics to water and wastewater network management. The network simulated is that of a typical Canadian water utility that has under invested in maintenance. Model results show that with no proactive rehabilitation strategy the utility will need to substantially increase its user fees to achieve financial sustainability. This increase is further exacerbated when price elasticity of water demand is considered. When the utility pursues proactive rehabilitation, financial sustainability is achieved with lower user fees. Having demonstrated the significance of feedback loops for financial management of water and wastewater networks, the paper makes the case for a more complete utility model that considers the complexity of the system by incorporating all feedback loops.

## 1. Introduction

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

In Canada, recent federal and provincial government legislation requires public water agencies to be financially accountable by mandating new reporting requirements. New regulations include the Canadian Institute of Chartered

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Accountants Public Sector Accounting Board (PSAB) statement PS3150 that requires all municipalities, starting in January 2009, to report all tangible capital assets along with their depreciation on financial statements (CICA, 2007) and Province of Ontario Regulation 453/07 (Ministry of the Environment Ontario, 2007), developed under the Safe Drinking Water Act, that requires all public utilities prepare and submit yearly reports on the current and estimated future condition of water and wastewater infrastructure. The later also requires the preparation and publication of long-term water and wastewater sustainability financial plans. This is related to the concept of "sustainable urban water" emerging in other parts of the world. A key principle for these plans is that revenues should be sufficient to pay all expenses of providing services (Ministry of the Environment Ontario, 2007). In the United States, the Governmental Accounting Standards Board (GASB) Statement 34, in France Accounting Standard M49, and in Australia, the Australian Accounting Research Foundation Standard 27 specifies similar accounting practices to PSAB (see FHWA, 2000; Howard, 2001; and Barraque and LeBris, 2007).

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

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

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

Halfawy et al. (2006) reviewed the following commercial municipal asset management systems: Synergen, CityWorks, MIMS, Hansen, RIVA, Infrastructure 2000, and Harfan. They found the majority of existing commercial asset management software to focus on operational management (e.g., work orders, service requests) with little or no functionality to support long-term renewal planning decisions (e.g., deterioration modeling, risk assessment, life cycle cost analysis, asset prioritization). From the reviewed systems, RIVA, Harfan, and Infrastructure 2000 implemented some level of support for long-term renewal planning of specific assets, mainly pavement. The other four systems include condition assessment and rating modules. Most of these commercial software tools now incorporate PSAB and other legislation annual reporting requirements and have improved strategic long range asset, risk and budget management by forecasting the full life cycle of infrastructure assets. They also generate a life cycle cost and risk profile for each asset, determine the events that should be scheduled each period, as well as, the