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Development of a system dynamics model for financially sustainable management of municipal watermain networks

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ABSTRACT

This paper develops causal loop diagrams and a system dynamics model for financially sustainable management of urban water distribution networks. The developed causal loop diagrams are a novel contribution in that it illustrates the unique characteristics and feedback loops for financially self-sustaining water distribution networks. The system dynamics model is a mathematical realization of the developed interactions among system variables over time and is comprised of three sectors namely watermains network, consumer, and finance. This is the first known development of a water distribution network system dynamics model. The watermains network sector accounts for the unique characteristics of watermain pipes such as service life, deterioration progression, pipe breaks, and water leakage. The finance sector allows for cash reserving by the utility in addition to the pay-as-you-go and borrowing strategies. The consumer sector includes controls to model water fee growth as a function of service performance and a household's financial burden due to water fees. A series of policy levers are provided that allow the impact of various financing strategies to be evaluated in terms of financial sustainability and household affordability. The model also allows for examination of the impact of different management strategies on the water fee in terms of consistency and stability over time.

The paper concludes with a discussion on how the developed system dynamics water model can be used by water utilities to achieve a variety of utility short and long-term objectives and to establish realistic and defensible water utility policies. It also discusses how the model can be used by regulatory bodies, government agencies, the financial industry, and researchers.

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1. Introduction

Water supports socio-economic activities which have a direct bearing on the quality of life in human settlements. It is also a primary input in agricultural production and is used in industrial processes such as power generation, manufacturing and mining. Canada is endowed with an abundant supply of freshwater to meet such needs. With only 0.5% of the world's population, Canada has freshwater stocks and renewable water resources that are 20% and 7% of the corresponding world's totals, respectively (Simonovic and Rajasekaram, 2004). At 327 L per capita per day, Canadian water consumption is amongst the largest within the OECD countries (Environment Canada, 2010). The public perception of water abundance is a possible reason for the high residential water consumption in Canada. However, a more tangible reason is that the price of water has not reflected the full cost of providing water services (Renzetti, 1999). Swain et al. (2005) indicate that municipal governments utilized grants received from federal and provincial governments to install unnecessary capacity without passing on the cost to customers thereby encouraging overconsumption. Brubaker (2011) states that the expectation of grants motivates municipalities to avoid investing their own resources in maintenance of the infrastructure assets. The flow of grants has decreased substantially and is no longer an assured source of funding for municipal governments (El-Diraby et al., 2009). Incidentally, this happens at a time when components of water supply systems, especially pipes constituting the distribution networks, are approaching the end of their service life. The combination of an aging infrastructure, diminished funding resources, and years of neglect in infrastructure maintenance, appears to be a looming crisis (Mirza, 2007). To thwart such a scenario, new legislation and regulations was developed over the past decade as shown in Table 1 to force Province of Ontario and Canada municipal water utilities to better manage their water infrastructure assets.

It is argued that the intended goals of above mentioned regulations can only be realized when a holistic view of the water supply systems is adopted within the socio-political context in which these systems function. This implies that water supply systems are treated as complex systems in which physical resources (water, infrastructure) interact with people (consumers, utility management, political decision makers), and capital (financial resources). It is also argued that a change in one of these interacting system components does not remain isolated but effects changes in other parts of the system. Such unintended triggered changes often work against the original policy interventions (Forrester, 1969). Rehan et al. (2011) highlighted the interactions among physical, social, and financial components of urban water and wastewater networks using a simplified causal loop diagram and employed an aggregated system dynamics model to demonstrate quantitatively the significance of the interacting components. In a subsequent study (Rehan et al., 2013a, b), a detailed system dynamics model for management of wastewater collection networks was developed and applied to a case study.

In this paper, a causal loop diagram (CLD) and a system dynamics model for financially sustainable management of urban water distribution networks are presented. The developed CLD is a novel contribution in that it illustrates the unique characteristics and feedback loops for financially self-sustaining water distribution networks. The system dynamics model is a mathematical realization of the CLD that captures dynamic interactions among system variables over time. It is comprised of three sectors namely watermains network, consumer, and finance as shown in Fig. 1. This model is different from the earlier works by the authors (Rehan et al., 2011, 2013a) in several respects. First, the watermains network sector specifically accounts for the unique characteristics of watermain pipes such as service life, deterioration progression, pipe breaks, and water leakage that are different than those in the simplified and aggregated pipes sector (Rehan et al., 2011) and wastewater pipes sector (Rehan et al., 2013a). Second, the finance sector is improved to allow for cash reserving by the utility in addition to the pay-as-you-go and borrowing strategies provided in the previous works. Third, the consumer sector is refined to include additional endogenous controls on water fee growth. These controls involve modelling water fee growth as a function of service performance and a household's financial burden due to water fees (see Section 5.3 for details).

The presented model determines all expenditures arising due to various cost drivers involved in the provision of drinking water services. It determines the water fee based on full cost recovery by comparing expenditures with revenues. Several policy levers are provided in the model to enable exploration of different rehabilitation and financing strategies. The strategies can be compared with the help of physical, financial, and customer satisfaction performance indicators.

The following section briefly reviews current literature related to management of water distribution networks. Section 3 delineates the scope of this study. A causal loop diagram for the system is presented in Section 4. A system dynamics model is developed in Section 5 while Section 6 discusses how the model can be used. Conclusions are drawn in Section 7. The developed model will be used in future studies that demonstrate data requirements, parameterization of model variables, and use of policy levers for evaluation of alternative management strategies for a case study.

2. Literature review

Current asset management frameworks for water distribution networks involve analysis of watermain pipe data to predict remaining service life; comparison of costs of repair/rehabilitation alternatives over the pipe life cycles; and, prioritization of rehabilitation activities such that available financial resources can be leveraged to achieve maximum benefits (Grigg, 2012).

Rajani and Kleiner (2001) and Kleiner and Rajani (2001) reviewed physically based and statistical models developed for prediction of pipe service life. A chronological list of various studies suggesting rehabilitation strategies for water distribution networks is provided in Table 2. Decision support tools for prioritization of pipe rehabilitation activities can be