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Financially sustainable management strategies for urban wastewater collection infrastructure – development of a system dynamics model

R. Rehan [a], M.A. Knight [b,*], A.J.A. Unger [c], C.T. Haas [b]

[a] National Institute of Urban Infrastructure Planning, University of Engineering and Technology, Peshawar, Pakistan
[b] 200 University Avenue W., Department of Civil and Environmental Engineering, University of Waterloo, ON, Canada N2L 3G1
[c] 200 University Avenue W., Department of Earth and Environmental Sciences, University of Waterloo, ON, Canada N2L 3G1

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ABSTRACT

Causal loop diagrams are developed for wastewater collection networks to identify complex interactions and feedback loops among physical, financial, and social sectors. Causal loop diagrams are then incorporated into a novel system dynamics based decision support tool that can be used for financially sustainable management of wastewater collection networks. Data requirements to develop the decision support tool are discussed along with how can the decision support tool be used to manage a utility.

The presented causal loop diagram is the first known attempt to lay out the interrelationships among system components using a formal technique. The causal loop diagram establishes the existence of several interacting feedback loops and demonstrates that the management of wastewater collection networks constitutes a complex dynamic system for which traditional management tools are deemed inadequate. The use of causal loop diagrams can be useful to mitigate effects of the silo-based organizational culture prevalent in many water utilities.

The system dynamics model is the first known decision support tool to quantitatively simulate the influence of interrelationships and feedback loops in wastewater collection network management. The model is a mathematical representation of the causal loop diagram to capture cost drivers and revenues sources in the system. It also includes a set of policy levers which allows formulation of various financing and rehabilitation strategies. The model can be used to develop short- and long-term management plans. The impact of financing and rehabilitation strategies on system performance can be simulated and evaluated in terms of financial and service level metrics. The decision support tool can also be used by utilities to ensure essential data is collected and flows within organizational units.

1. Introduction

According to Statistics Canada (2006), about 80% of Canadians live in cities. Over the next 30 years, this proportion is expected to increase to over 90%. The economic prosperity and quality of life of Canadians is dependent on vital city infrastructure, such as, highways and roads; bridges and overpasses; water and wastewater systems; and other facilities (Harchaoui et al., 2004; Brox, 2008). Water distribution and wastewater collection networks are considered to be the 'life-lines' of cities as they deliver clean and safe drinking water to businesses and homes and collect contaminated water (wastewater) for safe disposal back into the environment. In Canada, the majority of these networks are owned and operated by municipal governments. Limited municipal financial resources have resulted in many cities to under invest in the preservation and rehabilitation of infrastructure assets (Mirza, 2007). Water and wastewater networks have especially suffered in this respect, compared to visible assets, since the former are hidden underground and out of sight (Brubaker, 2011). The deferred investments needed to repair and prevent deterioration of existing infrastructure assets have been accumulating rapidly. Mirza (2007) refers to this accumulated deferred investment as an infrastructure deficit. He reports that for water and wastewater systems, infrastructure deficit grew from \$21 billion to \$31 billion over the period from 1996 to 2007. Moreover, this deficit is in addition to the new needs of \$56.6 billion for these systems (Mirza, 2007).

As a result of neglect and inadequate investments, water and wastewater systems have continued to deteriorate, posing a threat to public health and the environment (Brubaker, 2011). This became tragically evident in the case of Walkerton, Ontario, where seven people lost their lives and thousands more became sick due to contamination of the municipal water drinking supply system (Brubaker, 2011). To protect human health, the Province of Ontario enacted the Safe Drinking Water Act 2002 as recommended by the Walkerton Inquiry Commission (Ministry of the Environment,

* Corresponding author. Tel.: +1 519 581 8835.
E-mail addresses: rashidrehan@nwfpuet.edu.pk (R. Rehan), maknight@uwaterloo.ca (M.A. Knight), aunger@uwaterloo. ca (A.J.A. Unger), chaas@uwaterloo.ca (C.T. Haas).

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2002). Among the several regulations made under the authority of this legislation, Regulation 453/07 deals with financial plans for municipal water systems. This new regulation requires all public water utilities to prepare and publish long-term financial plans. This has led all municipal councils to publish and attest to the financial sustainability of their water and wastewater systems (Ministry of the Environment, 2008). A key principle underlying the financial sustainability requirement is that revenues must be sufficient to pay all expenses required to provide the service (Ministry of the Environment, 2007). In addition to the new Ontario provincial regulations, public water utilities are also required to comply with new reporting requirements as enunciated in the Public Sector Accounting Board (PSAB) statement PS3150. Specifically PS3150 requires that all local governments in Canada, starting in January 2009, to report all tangible capital assets along with their depreciation on financial statements (CICA, 2007). It is anticipated that these new reporting standards will ensure that all decision makers will become aware of the full cost of services (operation, maintenance, renewal, replacement, financing) and rate-setting issues (CICA, 2007).

The major reason for ensuring financial sustainability based on full-cost recovery is to achieve economic efficiency (McNeill and Tate, 1991; Harris et al., 2002). Economically inefficient systems are ones that are operated, where user fees do not reflect the full cost of providing services. Historically, Canadian water utilities have relied on grants from senior levels of government and general sources of municipal income (such as property taxes) to cover operation, maintenance and renovation costs. For example, Renzetti (1999) reported that user fees accounted for only 37% and 66% of operational and capital expenditures respectively. In addition, user fees have been typically set to pay only operational expenditures with no funds to renew the system. Canadian water systems have been economically inefficient and overconsumption has been encouraged (Renzetti, 1999; Swain et al., 2005). The new Provincial and federal government regulations seek to address the inefficiency and overconsumption issue by not allowing water utilities' financial plans to be based on external sources of revenue (Regulation 453/07), and requiring explicit accounting for depreciation of capital assets (PS3150).

Water and wastewater services are deemed public goods due to their public health and environmental externalities (Harris et al., 2002). This implies that decision makers have to also consider affordability when setting user fees.

The challenges faced by water and wastewater utility managers include rejuvenating existing infrastructure assets while meeting demands of new growth; maintaining acceptable levels of service; complying with financial self-sustainability and other regulatory requirements; and, gaining the support of various stakeholders for their management policies. The situation is further compounded by the fact that these issues are inherently interrelated and cannot be addressed in isolation to each other (Ginley and Ralston, 2010). Such interrelationships for a water and wastewater utility are identified in Rehan et al. (2011) using the formal method of causal loop diagram. Rehan et al. (2011) shows that interrelationships give rise to feedback loops which are responsible for complex dynamic behavior. A demonstration system dynamics (SD) model is also presented to quantify the impact of feedback loops on management strategies of water and wastewater networks. The conceptual framework employed by Rehan et al. (2011) is illustrated in Fig. 1a. This framework is a high level representation of water and wastewater network management and consists of physical infrastructure, finance, and consumer sectors. Within the physical infrastructure sector, water and wastewater pipes are aggregated into a single combined system. The causal loop diagram developed illustrates only a few of several interacting feedback loops. Furthermore, financial sustainability was modeled as maintaining a zero fund balance only with no allowance for debt financing of capital projects or building up cash reserves.

To overcome the limitations of the framework presented by Rehan et al. (2011), it is necessary that the physical infrastructure sector (Fig. 1a) be separated into distinct wastewater and watermain pipes sectors. The focus of this study is the development of a conceptual framework for the management of the wastewater collection network shown in Fig. 1b. This is accomplished by the development of causal loop diagrams (CLDs) and a system dynamics model for management of municipal wastewater collection networks under the paradigm of financial self-sustainability.

Causal loop diagrams serve as a useful qualitative tool for developing an appreciation of interrelationships and feedback loops. This in turn leads to a better understanding of the system behavior. The system dynamics model is developed as a decision support tool that can help municipal water utilities devise strategic plans that shall fulfill regulatory obligations and meet customer expectations regarding user fees and quality of service. Section 2 provides an overview of research relevant to the management of wastewater collection networks while Section 3 delineates the scope of this study. In Section 4, a causal loop diagram for the wastewater system is developed. The system dynamics model is developed in Section 5 and data requirements to develop the model along with model uses are discussed in Section 6. Research conclusions are provided in Section 7.

2. Literature review

Decision support tools have been developed to aid utility managers in maintaining water and wastewater infrastructure assets at acceptable levels of service while reducing costs associated with provision of services. These tools include some or a combination of the following functionalities: collection and registration of data related to infrastructure components; assessment and grading of the asset conditions; analysis of data for predicting remaining service life; comparison of life-cycle costs for repair/rehabilitation alternatives; and, prioritization of rehabilitation activities that ensure maximum benefits at minimum costs (Grigg, 2003). A brief survey of decision support tools applicable to wastewater collection networks is provided in the following paragraphs.

Wastewater pipes are inspected using closed circuit television and zoom camera systems, sewer scanner evaluation technology, laser profilers, non-destructive and remote-sensing techniques, and multi-sensory systems (Wirahadikusumah et al., 1998; Costello et al., 2007; Rizzo, 2010). Recognizing the importance of managing the collected data, Halfawy and Figueroa (2006) present a GIS-based asset data repository for municipal infrastructure. Younis (2010) points out the heterogeneity of data from multiple sources and formats at different utilities. He offers a solution to this by presenting a framework for data integration using extensible markup language (XML) specifications and technologies.

Various condition rating protocols are available for wastewater pipes. Most Canadian municipalities either directly employ the protocol published by the Water Research Centre (WRc) in the United Kingdom or use it as a basis for their own customized protocols (Rahman and Vanier, 2004). According to the WRc protocol (WRc, 2001), pipes are assigned Internal Condition Grades (ICG) on a scale of 1–5 based on their structural and operational defect scores, where ICG 1 represents the best condition and ICG 5 represents the worst or collapsed state. Defect scores for pipes are usually assessed manually but efforts are being made to automate this process (Sarshar et al., 2008).

Baur and Herz (2002) use a cohort survival model to determine residual life expectancies of sewer pipes. The procedure involves organizing pipes into 'cohorts' that share common characteristics