NRC Publications Archive Archives des publications du CNRC

Drinking water infrastructure assessment: the National Research Council of Canada perspective

Kleiner, Y.; Rajani, B. B.; Sadiq, R.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

World Environmental and Water Resources Congress 2009 [Proceedings], pp. 1-10, 2009-05-17

NRC Publications Archive Record / Notice des Archives des publications du CNRC :

<https://nrc-publications.canada.ca/eng/view/object/?id=1c51d389-9d60-4b3d-870b-62f4ca0c0d25>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=1c51d389-9d60-4b3d-870b-62f4ca0c0d25>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

<http://irc.nrc-cnrc.gc.ca>

Drinking water infrastructure assessment: The National Research Council of Canada perspective

NRCC-51298

Kleiner, Y.; Rajani, B.B.; Sadiq, R.

June 25, 2008

A version of this document is published in / Une version de ce document se trouve dans:
World Environmental and Water Resources Congress 2009, Environmental and
Water Resources Institute (EWRI) of the American Society of Civil Engineers,
Kansas City, Missouri, May 17-21, 2009, pp. 1-10

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>

National Research
Council Canada

Conseil national
de recherches Canada

Canada

DRINKING WATER INFRASTRUCTURE ASSESSMENT: THE NATIONAL RESEARCH COUNCIL OF CANADA PERSPECTIVE

Yehuda Kleiner, Balvant Rajani and Rehan Sadiq, National Research Council of Canada

Abstract

The essence of infrastructure asset management and decision-making on its renewal/rehabilitation is a trade-off between system performance and cost. System performance criteria for water networks include quality, quantity and reliability, i.e., the water should be safe, with acceptable aesthetics, taste and odour; regular and peak demand (including fire flows) should be met with acceptable pressure and with minimal interruptions. Costs comprise capital investment in system design, installation and renewal, operation and maintenance (energy, materials, labour, monitoring, inspection, testing, repair), and indirect and social costs incurred due to failure (property damage, disruption, illness, etc.).

Several challenges need to be overcome in the development of an integrated decision framework for water distribution network. Mechanisms affecting system performance criteria are not all well understood. It is difficult to define and measure performance (which inherently comprises several non-commensurate and often conflicting criteria), let alone decide what level of performance is acceptable. It is also difficult to calculate the costs involved to achieve a specific level of performance. Substantial spatial and temporal variability is inherent in even a moderate-size network, and the collection of data on the performance and condition of these buried assets is often difficult and costly.

At the National Research Council of Canada we have identified the need to address these issues in a holistic way, and in the last 15 years have been involved in a continual effort, both independently and in collaboration with others, to put the pieces of the puzzle together. Although the state of knowledge has advanced significantly since we started, a lot still needs to be achieved. This paper describes our past and current research activities, views and vision for future activities in the field.

Overview

A trade-off between system performance and cost is the essence of decision making on the renewal of infrastructure systems. The general objectives of a water distribution network can be stated as the supply of water that is safe, with acceptable aesthetics, taste and odour; and regular and peak demand (including fire flows) should be met with acceptable pressure and with minimal interruptions. These general objectives are easy enough to understand but their quantification poses a significant challenge because it cannot be done directly but rather through indicators. There are literally hundreds of different performance/condition indicators that have been proposed in the literature by prominent institutions such as the USEPA (2002), the British Office of Water (OFWAT, 1998), the World Bank (Yepes and Dianders, 1996), the International Water Services Association (IWSA) (Alegre, 1999), and many others. This multitude of performance indicators is testament to the complexity involved. Mechanisms affecting the performance criteria are not well understood. It is difficult to define and measure performance, let alone decide what level of performance is acceptable. Furthermore, the costs involved comprise capital investment in system design, installation and renewal, operation and maintenance (energy, materials, labour, monitoring,

inspection, repair) and indirect and social costs resulting from failure (property damage, disruption, illness, etc.). It is difficult to calculate the costs involved to achieve a specific level of performance; and the collection of data on the performance and condition of these buried assets is difficult and costly. All these challenges and difficulties are exacerbated by substantial spatial and temporal variabilities inherent in even a moderate-size system.

The failure of a system is broadly defined as the inability to meet one or more of its performance criteria. The risk of failure can be defined as the expected magnitude of the consequences of failure, i.e.

$$\text{Risk of failure} = E(\text{failure consequence}) = f(\text{probability of failure, costs of failure}) \quad (1)$$

Figure 1 illustrates a general, high-level view of the framework within which a water distribution network is managed. In the following sections we shall provide details about NRC's efforts to address the various pieces in this holistic puzzle.

Figure 1. Holistic view of water distribution asset management

Structural deterioration of water mains and failure risk

As water mains age they deteriorate. This deterioration may be classified into two categories: (i) structural deterioration, which diminishes the pipes structural resiliency and

their ability to withstand the various types of stresses; and (ii) deterioration of pipe inner surfaces, resulting in diminished hydraulic capacity, degradation of water quality and even diminishing structural resiliency in cases of severe internal corrosion.

The probability of a water main failure due to structural deterioration can be estimated using physical (mechanistic) models (Rajani and Kleiner, 2001b) and/or statistical (empirical) models (Kleiner and Rajani, 2001a). Statistical models develop empirical relationships between the pipe, its exposure to the external and operational environments and its observed failure frequency while physical models endeavour to mimic realistic field conditions as well as external and operational environments. Empirical models typically over-simplify a complex reality in order to (hopefully) achieve “80% of the answer with 20% of the effort”. In contrast, physical models are more general but require a substantial amount of data to represent specific conditions and environments. These data are either unavailable or very costly to obtain for even a modest portion of a distribution network.

The costs of a water main failure event may be classified into three categories: (a) direct, (b) indirect, and (c) social costs. While direct costs are relatively easy to quantify in monetary terms, indirect costs may require much more effort, and social costs are often the most difficult to describe and assess. The magnitude of failure consequence is, strictly speaking, a random value because no two failures have the same consequences. Failures in small distribution mains are usually repaired with little effort and typically collateral damage is relatively small. Failures of large transmission mains are relatively rare, and because only few water utilities attempt to assess total failure damage there are currently insufficient data to assign probability distributions to failure costs.

Figure 2 illustrates qualitatively how these differences between small distribution mains and large transmission mains translate into different forms of management. As a pipe ages and deteriorates (without renewal), its probability of failure (or failure frequency) increases and the risk increases as well. Note that the risk is expressed as the present value (PV) of expected cost. At the same time, the discounted (or PV of) the renewal cost declines as pipe renewal is deferred. The total expected life-cycle cost typically forms a convex shape, whose minimum point depicts the optimal time of renewal (t^*). The top part of Figure 2 illustrates a typical case of small distribution mains, where the optimal time of renewal corresponds to a relatively higher failure frequency. In contrast, due to higher failure cost, the bottom part of Figure 2 illustrates that for large distribution mains the optimal strategy is to avoid failure altogether, i.e., *failure prevention*, rather than tolerate some acceptable frequency, i.e., *failure management*.

Note that Figure 2 illustrates idealized cases, where the minimum point on the convex curve is quite clear. There are cases where this curve is not as well behaved. When the ageing rate (i.e., the rate at which failure frequency increases) is similar in magnitude to the discounting factor, the convexity of this curve can become quite flat, and the point of minimum cost becomes less crisp. When the cost of failure is relatively low compared to the cost of renewal and the discounting factor relatively high, the curve can take the shape

Figure 2. Optimal renewal frequency for distribution mains (top) vs. transmission mains (bottom). Time scale not necessarily same in both graphs.

of the “hammock-chair” as described by Herz (1999), with no definite minimum, indicating that renewal could perhaps be postponed indefinitely.

Asset management of small-diameter distribution mains

At the NRC, we have focused on several aspects of asset management of small-diameter distribution mains, namely investigation of the mechanics of pipe failure, development of statistical/empirical methods to model historical breakage frequency and forecast it in the future, development of leak-detection technologies and investigation of other nondestructive testing (NDT) technologies for the efficient assessment of the condition of pipes.

Numerous approaches have been proposed to decipher historical failure patterns. Kleiner and Rajani (2001b) provided a comprehensive review of the major ones, and more have been published since. Through the investigations of different aspects of the mechanical processes leading to pipe failure (e.g., Rajani and Tesfamariam, 2004; Tesfamariam *et al.*

2006.) we have developed an understanding of what factors need to be considered in asset management models for small distribution mains, which are based on empirical observations. Consequently, we have developed D-WARP (Distribution – Water Main Renewal Planner) and later I-WARP (Individual – Water Main Renewal Planner). Both D-WARP and I-WARP allow the consideration of time-dependent factors, such as climate effects, cathodic protection practices, etc. to be considered in the analysis of failure patterns. While D-WARP deals with high-level planning of groups (or cohorts) of water mains, I-WARP uses a nonhomogeneous Poisson process to model and forecast breakage frequency of individual water mains.

Climatic covariates that are used by both D-WARP and I-WARP are freezing index and rainfall deficit. Freezing index (*FI*) is a surrogate measure for the severity of winter, and rain deficit (*RD*) is a surrogate measure for soil moisture. *RD* can be considered in two separate forms. Cumulative *RD*, which is a measure of the average soil moisture over a given time period, corresponds to the effects described by Rajani *et al.* (1996). Snapshot *RD*, which is a measure of the soil moisture during winter, when the soil is mostly frozen, corresponds to the effects described by Rajani and Zhan (1996).

Cathodic protection can be defined as “... the reduction or elimination of corrosion by making the metal a cathode by means of an impressed direct current or attachment to a sacrificial anode (usually magnesium, aluminium or zinc)” (NACE, 1984). In practice, water utilities can implement two cathodic protection strategies, namely, hotspot and retrofit CP. Hotspot CP (HSCP) is the practice of opportunistically installing a protective (sacrificial) anode at the location of a pipe repair. These anodes are typically installed without any monitoring and stay in the ground until total depletion, usually without replacement. Retrofit CP refers to the practice of systematically protecting existing pipes with galvanic cathodic protection. If the existing water main is electrically discontinuous (e.g., bell and spigot with elastomeric gaskets and no bridging) then an anode is attached to each pipe segment (typically 6 m or 20' length). If the water main is electrically continuous then usually a bank of anodes in a single anode bed can protect several contiguous pipe segments. Figure 3 illustrates, using D-WARP, how an HSCP program that was implemented in 1990 by an East Ontario (Canada) municipality affected the breakage rate in one of its pipe cohorts.

In addition to the aforementioned climate and cathodic protection covariates, I-WARP allows the consideration of user-defined time series that may have impacted historical breakage rates. For example, pumping station failures have been observed to impact failure rates (due to high transient pressures) in a municipality in Western Canada. The inclusion of an appropriate (qualitative) time series helped to ‘explain’ the resulting outlier breakage rates. Other time series that may impact breakage (or repair) rates are leak detection campaigns, changes in pressure regimes, etc.

D-WARP is available for free download at the NRC-IRC website (NRC-IRC, 2007). A detailed user manual as well as select publications provide detailed information about the model and its application. A complete technical report, as well as a prototype computer application of I-WARP will be available later in 2009 from WRF (Water Research

Figure 3 Effect of hotspot CP program on a cohort of cast iron mains.

Foundation – formerly known as the American Water Works Association Research Foundation – AwwaRF), which co-funded the research.

In the area of leak detection we have developed LeakFinderRT, which is a PC based system for locating leaks in all types of water pipes using the leak noise correlation method. It incorporates several new developments, most importantly an "enhanced" correlation function. LeakFinderRT is fully realized in software for PC running under Microsoft Windows. Leak noise is recorded using the PC's soundcard and then correlated via the Fast Fourier Transform (FFT). LeakfinderRT is now a fully commercialised technology, which provides affordable leak detection solutions for small and medium sized municipalities. Based on knowledge generated from leak detection work, a new acoustics-based method is currently in development to discern the average remaining wall thickness of buried pipes. This method has the potential to serve as a screening tool to prioritise some types of water mains for inspection.

In the area of NDT, we are in the early stages of developing a robotic underwater vehicle capable of carrying and manipulating multiple NDT sensors for inspection and early detection of defects in large pipes while in service.

Asset management of large-diameter transmission mains

As discussed earlier, large transmission mains typically have low failure rates but when they fail the consequences can be quite severe. This low rate of failure, coupled with the limitations of currently available inspection tools and high cost of inspection, have contributed to the current situation where most municipalities lack the necessary data to estimate directly or indirectly the deterioration rates of these assets and subsequently to make rational decisions regarding their renewal.

The condition assessment of a large transmission main comprises two steps. The first step involves the inspection of the main using direct observation (visual, video) and/or NDT techniques (radar, sonar, ultrasound, sound emissions, eddy currents, etc.), which reveal distress indicators. The second step involves the interpretation of these distress indicators to determine the condition of the main. This interpretation process is dependent upon the

inspection technique. Interpretation of the visual inspection results, although based on strict guidelines, can often be influenced by subjective judgment. The interpretation of NDT results on the other hand, is often complex (at times proprietary) and can be imprecise.

Managing the failure risk of large transmission mains requires a deterioration model to enable the forecast of the asset condition as well as its possibility of failure in the future. Significant research effort has been carried out in the last two decades to model infrastructure deterioration. The Markov deterioration process (MDP) is one approach that has gained prominence as exemplified by Madanat *et al.* (1997), Kleiner (2001) and others. Examples of other types of statistical models include Lu and Madanat (1994), Ramia and Ali (1997), Flourentzou *et al.* (1999), Ariaratnam *et al.* (2001) and others.

In recent years, increased research effort has been dedicated to the application of soft computing methods to assess infrastructure deterioration. Soft computing methods include techniques such as artificial neural network (ANN), genetic algorithms (GA), belief networks (BN), fuzzy sets and fuzzy techniques. Fuzzy techniques seem to be particularly suited to model the deterioration of buried infrastructure assets where data are scarce and cause-effect knowledge is imprecise. Consequently, we have developed the T-WARP (Transmission – Water Main Renewal Planner) to assess risk of transmission pipelines combining the advantages of both the Markov deterioration process and fuzzy logic.

A fuzzy set describes the relationship between an uncertain quantity x and a membership function which ranges between 0 and 1. A fuzzy set is an extension of the traditional set theory (in which x is either a member of set A or not) in that an x can be a member of set A with a certain degree of membership. Fuzzy techniques help address deficiencies inherent in binary logic and are useful in propagating uncertainties through models.

Membership functions are often represented by triangular fuzzy numbers (TFN), which permit the use of linguistic variables. To illustrate the concept, suppose that the age of a pipe is defined by five fuzzy subsets (or numbers), each representing an age grade; $A_1 = \text{“new”}$, $A_2 = \text{“young”}$, $A_3 = \text{“medium”}$, $A_4 = \text{“old”}$ and $A_5 = \text{“very old”}$, as illustrated in Figure 4. The fuzzy subset A_3 “medium” for example, has a membership function such that for age x below 20 years or above 60 years the membership to “medium” is zero, and for age between 20 and 60 years the membership follows straight lines that form a triangle. Fuzzy set A comprises the collection of the five subsets (or numbers) A_i . Further, a crisp (exact) pipe age can be mapped onto the fuzzy set A so that it has memberships of 0.52 and 0.4 to age grades *medium* and *old*, respectively (Figure 4).

In our so-called fuzzy –Markov deterioration approach we use the concept of fuzzy rules that define relationships between variables by means of fuzzy *if-then* propositions. For example: “If ‘pipe’ is *old* and ‘pipe condition’ is *good* then ‘deterioration’ is *slow*”, where *old* and *good* and *slow* are linguistic constants represented by fuzzy sets (as in the age example above). An inference can be made, using the Mamdani (1977) algorithm, about how fast deterioration is if the pipe is only partially *old* (say 50% *old* and 50% *medium*) and its condition is only partially *good*. This method has the capacity to capture qualitative and highly uncertain knowledge. To describe the condition of the pipe we used a seven-grade fuzzy set: *excellent*, *good*, *adequate*, *fair*, *poor*, *bad*, and *failing*. The fuzzy Markov deterioration process is illustrated in Figure 5.

Figure 4. Example of fuzzy sub-sets (numbers).

Figure 5. Fuzzy Markov deterioration curves.

As the pipe deteriorates, memberships “flow” from a given condition state to a worse one. The transition process is governed by a set of fuzzy rules (rather than transition probabilities as in the traditional Markov process), which is constructed based on expert opinion. Once deterioration curves are determined they are used to estimate the time in the future when the pipe is expected to approach the *failing* state. The deterioration model can be re-calibrated with each additional inspection and condition assessment. Any pipe inspection, whether visual, NDE or other reveals evidence about the existence and extent of distress indicators on the pipe. These distress indicators have to be interpreted and translated into the fuzzy condition states space described earlier. A condition assessment framework for translating the distress indicators into fuzzy condition states is described in detail by Rajani *et al.* (2006). Kleiner *et al.* (2006a) provide details on fuzzy Markov deterioration. Kleiner *et al.* (2006b), provide details on how to combine fuzzy deterioration

with fuzzy consequences into a life-cycle fuzzy risk of failure. A prototype software application of T-WARP is available from WRF, which co-funded the research.

Water quality deterioration in distribution pipes

Numerous factors affect water quality in the distribution network and interactions amongst them are complex and often not well understood. Water quality failures in distribution networks are scarce, which make it difficult to establish statistically significant generalizations. In such data-sparse circumstances, expert knowledge and judgment can serve as a supplement or even as alternative source(s) of information. Q-WARP (water Quality – Water Main Renewal Planner) is a proof-of-concept model to predict water quality changes in distribution pipe networks, developed at the NRC with co-funding from WRF (Sadiq *et al.*, 2009).

Several mechanisms can compromise water quality within a distribution network. These include (Kleiner, 1998): (1) Intrusion of contaminants into the distribution network through system components whose integrity is compromised or through misuse or cross-connection or intentional introduction of harmful substances in the water distribution network. (2) Formation of corrosion byproducts and leaching of chemicals from the internal pipe surface. (3) Regrowth of microorganisms in the distribution network. (4) Formation of disinfection byproducts (DBPs) and loss of residual disinfectants; and (5) Permeation of organic compounds from the soil through plastic components into the distribution network.

Q-WARP uses a soft computing technique called ‘fuzzy cognitive maps’ (FCM) to model causal relationship between the numerous factors influencing water quality in the distribution network. FCM is a cyclical graph comprising nodes and arcs (edges), as illustrated in Figure 6. Influencing factors are represented by nodes C_i and causal relationships are represented by directed arches. $w_{ij} \in [-1, 1]$ represents the nature and strength of the relationship between ‘causal factor’ i and ‘effect factor’ j and the sign

Figure 6. An example of a fuzzy cognitive map (FCM)

Figure 7. Modular FCM for predicting ‘potential for contaminant intrusion’

Modular FCMs

Supervisory FCM

Figure 8. Two-tier (modular and supervisory FCM) framework

represents the type of causation. A positive causality is implied when $w_{ij} > 0$, where an increase in the value of i causes an increase in the value of j and vice versa. A negative causality is implied when $w_{ij} < 0$, where an increase in the value of i causes a decrease in the value of j and vice versa; and $w_{ij} = 0$ implies no causal relationship between i and j . Q-WARP is in fact a rule-based FCM, where causal relationships are defined by rules (e.g., ‘if C_1 is high then C_2 is medium’) similar to the rules described in the previous section.

Figure 7 illustrates the FCM representing processes leading to contaminant intrusion. The M_i gates represent rule sets that govern relationships between the various factors. Experience shows that if FCM are very large and ‘democratic’ (every node can be connected to every other node) they become insensitive to perturbations in inputs. Consequently, Q-WARP is designed as a two-tier framework, as is illustrated in Figure 8. Each of the six modular FCMs in tier 1 (representing six different WQ failure mechanisms) is in fact a FCM similar to the one illustrated in Figure 7 for contaminant intrusion. The outputs of the six modular FCMs flows into the supervisory FCM, whose output in turn yield the over potential for water quality failure. A full report on Q-WARP as well as a prototype software application is available from the WRF (Sadiq *et al.*, 2009).

Final remarks

In general, the industry seems to be progressing in the right direction despite many challenges and inherent complexities in the management and operations of water supply and distribution systems. Much progress has been made in the understanding of deterioration processes and failure modes. At the same time, as practices change and new materials are used, the knowledge gap, while decreasing from one end is increasing from the other. However, despite all these advances, too many water utilities still are not aware of the benefits of collecting and organising data that can be used in the various deterioration and decision support models.

As NDT techniques evolve, including the development of various sensors and robots, it appears that failure anticipation and prevention is likely to become technologically feasible as well as affordable. Currently, it seems that only mains prone to high-cost failure (namely transmission mains) can justify the use of these techniques, but this situation is likely to change over time. In the meantime, while the bulk of water distribution networks are comprised of small mains with relatively low failure consequences, NDT techniques can, in some circumstances, be used as complementary means to the empirical models, which rely on historical break records.

REFERENCES

- Alegre, H., 1999. “Performance Indicators for Water Supply Systems – Current Trends and On-going Projects”, pp. 148-178, *Drought Management Planning in Water Supply Systems*, Ed. by Carbera, E., and Garcia-Serra, J., Kluwer Publishers, Netherlands.
- Ariaratnam, S.T., El-Assaly, A. and Yang, Y. 2001. “Assessment of infrastructure needs using logistic models”. *Journal of Infrastructure Systems*, ASCE, 7(4): 160-165.
- Flourentzou, F., E. Brandt, and C. Wetzel. 1999. “MEDIC – a method for predicting residual service life and refurbishment investment budget”. *Proceedings of the 8th*

- conference *Durability of Building Materials and Components*, Edited by M.A. Lacasse and D.J. Vanier, NRC, pp. 1280-1288, Vancouver.
- Herz, R. 1999. "Bath-tubs and hammock-chairs in service life modelling". *Proceedings of the 13th European Junior Scientist Workshop*, pp. 11-18.
- Kleiner, Y. 1998. "Risk factors in water distribution systems". *British Columbia Water and Waste Association 26th Annual Conference*, Whistler, BC, Canada.
- Kleiner, Y. 2001. "Scheduling inspection and renewal of large infrastructure assets", *Journal of Infrastructure Systems*. ASCE, 7(4): 136-143.
- Kleiner, Y. and Rajani, B.B. 2001a. "Comprehensive review of structural deterioration of water mains: statistical models". *Urban Water*, 3(3): 131-150.
- Kleiner, Y.; Rajani, B.B.; Sadiq, R. 2006a. "Modelling the deterioration of buried infrastructure as a fuzzy Markov process," *Journal of Water Supply Research and Technology: Aqua*, 55, (2), pp. 67-80.
- Kleiner, Y.; Rajani, B.B.; Sadiq, R. 2006b. "Failure risk management of buried infrastructure using fuzzy-based techniques". *Journal of Water Supply Research and Technology: Aqua*, 55, (2), pp. 81-94.
- Lu, Y. and Madanat, S.M. 1994. "Bayesian updating of infrastructure deterioration models". *Transportation Research Record* 1442: 110-114.
- Madanat, S.M., Karlaftis, M.G., and McCarthy, P.S. 1997. "Probabilistic infrastructure deterioration models with panel data". *Journal of Infrastructure Systems*, ASCE, 3(1): 4-9.
- Mamdani, E.H. 1977. "Application of fuzzy logic to approximate reasoning using linguistic systems", *Fuzzy Sets and Systems*. 26: 1182-1191.
- NACE. 1984. "Corrosion Basics – An Introduction". *National Association of Corrosion Engineers*, Edited by A. deS. Brasunas.
- NRC-IRC, 2007. http://irc.nrc-cnrc.gc.ca/ui/software/dwarp/index_e.html
- Office of Water (OFWAT) 1998. "Comparing Company Performance". *OFWAT Information Note No. 5*, London, England.
- Rajani, B.B.; Kleiner, Y.; Sadiq, R. 2006. "Translation of pipe inspection results into condition rating using fuzzy synthetic valuation technique," *Journal of Water Supply Research and Technology: Aqua*, 55, (1), pp. 11-24.
- Rajani, B. and Zhan, C. 1996. "On the estimation of frost load." *Canadian Geotechnical J.*, 33(4): 629-641.
- Rajani, B.B. and Kleiner, Y. 2001b. "Comprehensive review of structural deterioration of water mains: physical models". *Urban Water*, 3(3): 151-164.
- Rajani, B.B. and Tesfamariam, S. 2004. "Uncoupled axial, flexural, and circumferential pipe-soil interaction analyses of partially supported jointed water mains", *Canadian Geotechnical Journal*, 41(6): 997-1010.

- Ramia, A.P. and Ali, N. 1997. "Bayesian methodologies for evaluating rutting in Nova Scotia's special B asphalt concrete overlays". *Canadian Journal of Civil Engineering*, 24(4): 1-11.
- Sadiq, R., Kleiner, Y. and Rajani, B. 2009. "Proof-of-concept model to predict water quality changes in distribution pipe networks (Q-WARP)". Water Research Foundation, Denver, CO (forthcoming)
- Tesfamariam, S., Rajani, B.B. and Sadiq, R. 2006. "Possibilistic approach for consideration of uncertainties to estimate structural capacity of ageing cast iron water mains", *Canadian Journal of Civil Engineering*, 33(8): 1050-1064.
- US EPA, 2002. "Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems". EPA/600/R-02/029, US Environmental Protection Agency, Washington DC.
- Yeppes, G., and Dianderas, A. 1996. "Water and Wastewater Utilities Indicators". *Water and Sanitation Division, World Bank*.