A decision support tool for water mains renewal for small to medium sized utilities: a risk index approach
Alex Francisque, Anjuman Shahriar, Nilufar Islam, Getnet Betrie, Riffat Binte Siddiqui, Solomon Tesfamariam and Rehan Sadiq

ABSTRACT
All over the world water mains are under increasing threat due to aging, aggressive environmental factors, operational factors and inadequate maintenance. Extensive maintenance, repair and rehabilitation practices, or replacement of water mains are required to ensure an acceptable performance of water supply systems. Investment deficit for water system maintenance and rehabilitation has been estimated in billions. Small to medium sized water utilities are generally impacted more because of limited financial resources and lack of technical expertise. However, water mains integrity is of primary interest due to potential adverse consequences related to public health, safety, and heavy financial liabilities in case of a failure. This paper presents a user-friendly decision support tool to help managers of these water utilities to prioritize maintenance, repair, and replacement (M/R/R) strategies for water mains. This paper proposes a risk index approach which aggregates the water mains vulnerability and associated failure consequences. The developed tool can help decision-makers to rank the water mains and help to prioritize M/R/R strategies. The results have been integrated with a geographic information system that will allow a decision-maker to visualize the vulnerable zones within the network. The City of Kelowna water network is used to demonstrate the proposed approach.

Key words | decision-making, decision support tool, risk index, water mains, water supply

INTRODUCTION
Most water supply infrastructures in Canada have reached the end of their design life in Canada as they were installed between 1950 and 1970 (National Guide to Sustainable Municipal Infrastructure (NGSMI) 2003; Mirza 2007). The investment deficit for water system maintenance and rehabilitation was estimated to be $11.1 \times 10^9$ in 2007, and has been increasing year after year (Mirza 2007). This gap will impact mostly small to medium sized municipalities since these utilities lack technical, managerial, and financial resources (United States Environmental Protection Agency (USEPA) 2003). Moreover, water mains are typically 60-80% of a water supply network (WSN) (Sadiq et al. 2009; National Research Council (NRC) 2010), and they are difficult to inspect because most of them are buried underground. Often water mains are annually rehabilitated and replaced based on preventive and/or corrective actions (Kanakoudis & Tolikas 2001, 2004; Christodoulou et al. 2009). It is therefore crucial for the managers of such water utilities to have a simple and efficient tool that can allow them to prioritize their interventions and allocate their limited human and financial resources.

Sadiq et al. (2010) highlighted that assessment of water main conditions entails consideration of ‘readiness of a component to serve its purpose’. Imran et al. (2007) defined water supply infrastructure integrity as its ability to transport water in an acceptable quantity and quality and with minimal interruption (continuity), which is also the ultimate purpose of water mains (Kanakoudis & Tolikas 2004). Water mains failure may manifest in terms of increasing pipe breakage rate, decreasing hydraulic capacity, and...
continuously degraded water quality (Kanakoudis 2004a; Lounis et al. 2010). They are subjected to failure due to aging coupled with continuous stress from operational and environmental loads (e.g., regular temperature variations and soil moisture variations due to precipitation, and climate change effects). Failures of water mains may cause significant health and socio-economic impacts that may adversely affect public confidence (NRC 2009). The deterioration of water mains leads to structural failure that has grave economic consequences due to loss of treated water, flooding of streets and sometimes homes, problems of contaminant intrusion into the distribution network (Kirmeyer et al. 2004), loss of business, and costs associated with emergency response (Makar & Kleiner 2000; NGSMI 2003). In some countries more than 50% of the supplied water is lost through leaks and breaks (Kanakoudis et al. 2011). The drinking water loss through leakage due to water mains failure is a growing concern in Canada (Farley & Trow 2005). For example, the non-revenue water loss is estimated to be ∼15% (Kingdom et al. 2006). The deterioration of water quality initiated by contaminant intrusion can adversely affect consumers’ health as well as the aesthetic properties of the water (e.g., taste, odor, and color) (Snow 1885; Ontario Ministry of the Attorney General (OMAG) 2002; Medema et al. 2003; Sadiq et al. 2010). Therefore, prioritization of water mains for replacement requires not only consideration of their structural integrity and hydraulic capacity, but also the consideration of water quality. Note that in this paper the terms ‘water main’ and ‘pipe’ are interchangeably used.

There are many approaches for modeling water main deterioration in a WSN. Marlow et al. (2009) provide a detailed review of the approaches. The models are usually grouped into four groups: the deterministic models (e.g., Shamir & Howard 1979; Randall-Smith et al. 1992; Rajani & Tesfamariam 2004), statistical models (e.g., Giustolisi et al. 2007; Berardi et al. 2008; Tabesh et al. 2009; Kleiner & Rajani 2010; Tsitsifili & Kanakoudis 2010; Kanakoudis & Tsitsifili 2011; Rogers 2011; Tsitsifili et al. 2011), physical probabilistic models (e.g., Ahamed & Melchers 1994; Rajani & Makar 2000; Davis et al. 2007), and soft computing or artificial intelligence models (e.g., Kleiner et al. 2006; Rajani et al. 2006; Achim et al. 2007). Literature about statistical models is very abundant. Kleiner & Rajani (2001) provide a comprehensive review of various statistical models developed before 2001 while Nishiyama & Fillon (2013) make a review of these models from 2002 to 2012.

Many of the pipe deterioration models use few intrinsic pipe characteristics to forecast future deterioration. However, considering environmental and operational parameters in addition usually makes a failure prediction more accurate and realistic. The risk-based approach which combines the asset deterioration forecasted by one of the previous methods with the associated potential consequences has been popular for asset management. It provides a more robust alternative to the traditional cost/benefit approach, particularly for water supply systems where public safety and public health are of prime importance.

Kanakoudis (2004b), Kanakoudis & Tolikas (2004), and Kanakoudis et al. (2015) have developed methodologies that hierarchically analyze possible preventive maintenance policy and actions as well as healing measures. In this paper, a decision support tool (DST) based on risk assessment has been proposed to allow utility managers assessing the likelihood of a system failure, to consider its structural integrity, hydraulic capacity and water quality, and the failure consequences. The DST uses an appropriate forecasting model to project the expected pipe future condition and the likelihood of its failure based on condition assessment results in order to make decisions for small to medium water utilities, where relevant data are limited. The DST named Water main Replacement Risk-based Model (WARRM) will help to prioritize the maintenance/repair/replacement (M/R/R) strategies of water mains by ranking the water mains using a risk index. Furthermore, the WARRM is integrated with a geographic information system (GIS) to help with visualizing, among other aspects, the concentration of at risk pipes/zones in the network. The next two sections describe the proposed approach and area of the case study. The last two sections present and discuss the results obtained for the case study and the main conclusions of this study.

THE PROPOSED APPROACH

The general framework consists of five levels and it is done in a hierarchical fashion as shown in Figure 1. Level-1 consists of the risk index (RI) and risk management (RM). Level-2 comprises the vulnerability index (VI) and
consequence index (CI). Level-3 consists of the hydraulic capacity index (HCI) and structural integrity index (SII). Level-4 is formed by the water aggressiveness index (AI), soil corrosiveness index (SCI), and structural failure index (Str.FI). Level-5 includes some basic input parameters. The water quality index (WQI) presents a certain particularity in terms of its location in the framework hierarchy. As a poor water quality does not necessarily mean water main failure, the WQI is only associated to the RI assessed (at Level-1) to favor appropriate risk management. In the following subsections, the input parameters and indices of the framework as well as the transformation method of measured or estimated values to index values are presented.

**Input parameter**

A summary of the input parameters used in this study is presented in Table 1. This table shows the name of the parameters, their unit, a brief description of each parameter and for which index the parameter is used as an input. These parameters are selected from parameters generally used to predict pipe deterioration based on the principle of parsimony.

**Parameter transformation and weight computation**

Each input parameter with its unit (dimension) is defined except pH, which is dimensionless. Therefore, to aggregate them transformation functions are used to convert their values into a uniform scale between zero and one (i.e., [0 1]), where zero refers to good and 1 to bad. Swamee & Tyagi (2000) proposed various transformation functions that allow, by using appropriate threshold values, conversion of the values of non-commensurate parameters (or variables) into a homogeneous scale in order to aggregate them. For simplicity, in this research linear and unimodal transformation functions have been used.

To define the appropriate threshold values and their margins for each input factor/parameter the authors have focused on various criteria including, to name a few, the nature of the parameter and its impacts on the final or intermediary output...
Table 1 | Brief description of the parameters selected for developing the risk index model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>year</td>
<td>The installation date or the water main age is reported as the most important parameter in most of the literature (Kleiner &amp; Rajani 2002; Hu &amp; Hubble 2007; Berardi et al. 2008) causing pipe deterioration.</td>
</tr>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>Water main with larger diameter is expected to have greater thickness compared to smaller diameter water main. An inverse relation between the diameter and structural integrity is anticipated from different studies. However, a large-diameter water main is intended to carry a huge amount of water to satisfy customer demand. Thus, in the event of a large-diameter pipe failure, the potential consequences will be more important (Makar &amp; Kleiner 2000; USEPA 2009).</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
<td>Greater pipe length can have beam failure in the water main and therefore, has been considered as one of the basic static parameters (Hu &amp; Hubble 2007). However, the longer a water main is literally the more important it is for the network and consequences will be higher.</td>
</tr>
<tr>
<td>Soil resistivity</td>
<td>Ω-cm</td>
<td>Low resistivity (&lt;1,500 Ω-cm) will result in a higher corrosion rate probability, while high resistivity (&gt;3,000 Ω-cm) results in a lower corrosion rate probability (Rossum 1969; Sadiq &amp; Husain 2005; Sadiq et al. 2005; Restrepo et al. 2009).</td>
</tr>
<tr>
<td>Redox potential</td>
<td>mV</td>
<td>The redox potential essentially is a measure of the degree of aeration in a soil. A high redox potential indicates high oxygen content. Low redox values may provide an indication that conditions are conducive to anaerobic microbial activity (Sadiq &amp; Husain 2005).</td>
</tr>
<tr>
<td>Soil moisture content</td>
<td></td>
<td>Moisture content according to drainage condition is important to determine soil corrosiveness. Poor drainage sometimes causes a high possibility of pipe corrosion.</td>
</tr>
<tr>
<td>% Fines</td>
<td></td>
<td>There is a correlation between percentage of clay (soil particle &lt;0.002 mm) and the drainage condition, soil movement behavior, and presence of sulfate-reducing bacteria in soil. All those properties play an important role in causing corrosion.</td>
</tr>
<tr>
<td>% Gravel</td>
<td></td>
<td>Gravel percentages have been proposed to estimate the soil effects on plastic pipes.</td>
</tr>
<tr>
<td>Soil pH</td>
<td></td>
<td>Soil pH is a measure of the acidity or alkalinity in the soil. The pH level of the soil can directly and indirectly affect its corrosiveness (Sadiq &amp; Husain 2005; Sadiq et al. 2005).</td>
</tr>
<tr>
<td>Soil sulfide content</td>
<td>mg/kg</td>
<td>In metallic pipe deterioration, microbiological corrosion might be an important component. Generally, sulfides are reported as positive, trace and negative (Doyle 2000; Sadiq &amp; Husain 2005; Sadiq et al. 2005).</td>
</tr>
<tr>
<td>Water hardness</td>
<td>mg/L (CaCO₃)</td>
<td>Water hardness is important for cementitious water mains as it represents the aggressiveness of water which may cause wall leaching and deterioration.</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>mg/L (CaCO₃)</td>
<td>Same effect as water hardness.</td>
</tr>
<tr>
<td>Water pH</td>
<td></td>
<td>Same effect as water hardness and total alkalinity, except, it has an impact on metallic water mains (Yamini &amp; Lence 2010).</td>
</tr>
<tr>
<td>Water age</td>
<td>Hour</td>
<td>Water age represents the water quality condition.</td>
</tr>
<tr>
<td>Water velocity</td>
<td>m/s</td>
<td>Water velocity is indirectly related to the hydraulic capacity as a specific range of water velocity should be maintained.</td>
</tr>
<tr>
<td>FRC</td>
<td>mg/L</td>
<td>FRC can represent the water suitability for consumption as it ensures microbial inactivation (Rodriguez et al. 2005). Various studies have also reported a positive correlation of this parameter to internal corrosion and water main deterioration (Tamminen &amp; Ramos 2008; Yamini &amp; Lence 2010).</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>Turbidity is also a commonly used parameter to represent water quality.</td>
</tr>
<tr>
<td>Color</td>
<td>ACU</td>
<td>Color is also a water quality parameter.</td>
</tr>
<tr>
<td>Pressure</td>
<td>m</td>
<td>Water pressure can be used as a surrogate measure for hydraulic failure as it can represent hydraulic capacity failure, inadequate water supply to the customers, and possible water quantity loss by leakage (Wood &amp; Lence 2005; Rogers 2011).</td>
</tr>
</tbody>
</table>

(continued)
in terms of magnitude (weak, strong, etc.) and direction (input increase is good for the output (i.e., a benefits factor) or otherwise (i.e., a cost factor)), its general and actual or specific (according to the case under study) range of variability, and, if applicable, the regulation standards, guidelines, or recommendation values for the parameter provided by regulation organizations such as USEPA, World Health Organization (WHO), and Health Canada. For example, free residual chlorine (FRC) and turbidity which are both related to the water microbial quality (Payment et al. 2005), among others. However, all else being equal, the link is more explicit with the chlorine concentrations, its impacts are stronger and its increase is good for the bacterial quality of the water (Zhang & DiGiano 2002; Huck & Gagnon 2004; Ndiongue et al. 2005; Francisque et al. 2009a). Once the standard target concentration at the exit of the treatment plant (USEPA 1989) is satisfied, ranges of chlorine concentrations within the distribution networks differ considerably from one network to another. Chlorine demands are highly variable (uncertain), from one network to another and even in the same network, temporally as well as spatially. In contrast, turbidity levels vary less from one network to another and in the same network. For some distribution networks, due to treatment plant deficiencies managers have to use high chlorine doses to satisfy high chlorine demands. For such networks the threshold values for FRC must take into account its high concentrations to maintain the water bacterial stability within the network. Due to this large uncertainty in chlorine demands, regulations are more precise about turbidity than chlorine in water distribution networks.

Moreover, it is important to highlight that the same parameter can be seen as a completely ‘different’ one (cost or benefits) according to the output it impacts. Chlorine can once again be taken as an example: when the output is the water aggressiveness on metallic pipes, chlorine becomes a cost factor (high concentrations are not good for the pipes), the magnitude of its impact is less known, there is no regulation, etc.; all this led to the choice of a different set of threshold values than those set when chlorine is used in water quality assessment. All those particular situations combined with the authors’ experience have led to the choice of the thresholds used in this research. Interested readers can also consult the work published by Francisque et al. (2009b) in which many of the parameters involved in the present research were used as input factors for prioritizing monitoring locations in a water distribution network based on a fuzzy risk approach, but in general with different threshold values. Table 2 shows the threshold values of each input parameter used for developing the transformation functions for the case under study. Based on the distribution of each index value between the interval [0 1] and the authors’ experience, two cut-off values have been defined for each parameter for grouping the index values into three classes: low, medium, and high.

A different transformation approach was followed for land use (LU), density of population (DP), pipe diameter (D), and length (L) parameters. The LU values are unitless and already belong to [0 1] due to the way the values were computed. The DP values were grouped into 10 classes then transformed into [0 1] based on the population density ranges provided by Contreras (2007) as shown in Table 3(a). A similar approach to DP was used for pipe diameter and length (Table 3(a)).

Once the transformed values were obtained from the transformation functions, a preference weight was assigned to each parameter/index for aggregation. The preference weights (Table 3(b)) are assigned to each parameter and index using the analytic hierarchy process (AHP) developed by Saaty (1988). AHP is a pairwise comparison method used to estimate the preference weights ($w_i$, $i = 1, 2, \ldots, n$) of each parameter in a group of $n$ parameters; the sum of $w_i$ for $n$
The pair-wise comparison can be fine-tuned and calibrated to meet the stakeholders’ need.

**Index computation**

**Structural failure index**

Pipe Str.FI is estimated from pipe diameter, age, and length using a non-linear multiple regression analysis method. This statistical method was used to predict water main breakage rate. Equation (1) provides the relationship showing the pipe breakage rate ($\tau$) as a function of pipe diameter ($D$), age ($A$), and length ($L$). The coefficients $a$, $b$, $c$, $d$, $e$, $f$, $g$, $h$, $i$, and $j$ are the regression coefficients.

$$
\tau = a + bD + cA + dL + eD^2 + fA^2 + gL^2 + hD \times A \\
+ iA \times L + jL \times D
$$

Note that the pipe diameter, age and length used in the above equation represent pipes that have been clustered.

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**Table 2** | Threshold values used for developing transformation functions for different parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values of the parameter ($x$: abscissa) and corresponding index values ($y$: ordinate)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil corrosiveness</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Metallic pipe score | Abscissa ($x$) values (Points) 0 4.5 $\geq$ 14  
Ordinate ($y$) values 0 0 1 |
| Cementitious pipe score | Abscissa ($x$) values (Points) 0 3 $\geq$ 7  
Ordinate ($y$) values 0 0 1 |
| Plastic pipe score | Abscissa ($x$) values (Points) 0 2 $\geq$ 7  
Ordinate ($y$) values 0 0 1 |
| **AI** | | |
| Water pH (for metallic pipes) | Abscissa ($x$) values 0 5.5 $\geq$ 8.8  
Ordinate ($y$) values 1 1 0 |
| 4FRC (for metallic pipes) | Abscissa ($x$) values (mg/L) 0 0.3 0.65 $\geq$ 1  
Ordinate ($y$) values 0 0.8 1 |
| AC pipes (AI = pH + log [AH]) | Abscissa ($x$) values [0 10] [10 12] $\geq$ 12  
Ordinate ($y$) values 1 0.5 0 |
| **Hydraulic capacity (HC) modeling** | | |
| Water pressure | Abscissa ($x$) values (m) $\leq$ 10 35 70 $\geq$ 120  
Ordinate ($y$) values 1 0 0 1 |
| Water velocity | Abscissa ($x$) values (m/s) $\leq$ 0.05 0.2 1 $\geq$ 1.5  
Ordinate ($y$) values 1 0 0 1 |
| **Water quality (WQ) modelling** | | |
| Water turbidity | Abscissa ($x$) values (NTU) 0 $\geq$ 1  
Ordinate ($y$) values 0 1 |
| Water color | Abscissa ($x$) values (TCU) 0 10 $\geq$ 15  
Ordinate ($y$) values 0 0.6 1 |
| 4FRC (mg/L) | Abscissa ($x$) values (mg/L) 0 0.1 0.3 0.8 $\geq$ 1.2  
Ordinate ($y$) values 1 1 0 0 1 |
| Water age | Abscissa ($x$) values (Hours) 0 24 $\geq$ 48  
Ordinate ($y$) values 0 0.3 1 |
| Breakage rate or Structural failure (Str.FI) | Abscissa ($x$) values (number of breaks/year/km) 0 1.5 $\geq$ 3  
Ordinate ($y$) values 0 0.5 1 |

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*It is important to note there are two different transformation functions for FRC. When FRC is related to AI for metallic pipes, low values are desirable for the pipe metal whereas high values are not. Therefore, an increasing linear transformation function is used. When FRC is related to water quality, low values are not good to inactivate and/or prevent growth or regrowth of microbes, and high values will favor more disinfection by-product formation (some are carcinogenic), bad taste and odor. It is good to have concentrations between the upper bound of low values and the lower bound of high values.*

*The values derive from regulation standards, and guidelines, or recommendation values of regulation organizations such as USEPA (2004), WHO (1993), and Health Canada (2009).*
Clustering pipes into homogenous classes is done because it is difficult to develop a statistical model for individual pipes when breakage rate data are limited (Andreou et al. 1987a, b; Herz 1996; Le Gat & Eisenbeis 2000; Kanakoudis & Tolikas 2004). The clustering method used by Berardi et al. (2008) has been adopted in this study. For each pipe type (i.e., plastic, cementitious, and metallic), the diameter was used to group the pipes into N classes; the interval within the group is 50 mm. Then the pipes are further classified using their age within each diameter class. Note that the pipe length was used as a weighting factor. The class equivalent age and diameter are computed using Equation (2). Thereafter, the total length and number of breaks as well as the number of breaks per year and per kilometer of pipe (#/year/km) per class are calculated as shown Table 4(b).

The breakage rates predicted by Equation (1) (for City of Kelowna water mains) are transformed on a scale between zero and one. Then these normalized values are distributed into three linguistic grades: low (Str.FI < 0.1), medium (0.1 ≤ Str.FI < 1) and high (Str.FI = 1) using two threshold values. All the threshold values used in the WARRM can be fine-tuned to meet the stakeholders’ need.

**Table 3a** | Classes used to transform population density, pipe diameter and length values into [0 1]

<table>
<thead>
<tr>
<th>Class</th>
<th>Population density</th>
<th>Pipe diameter</th>
<th>Pipe length</th>
<th>Granularity value into [0 1]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(persons/km²)</td>
<td>(mm)</td>
<td>(m)</td>
<td></td>
</tr>
<tr>
<td>&lt;10</td>
<td></td>
<td>&lt;41</td>
<td>&lt;11</td>
<td>0.1</td>
</tr>
<tr>
<td>[10 25]</td>
<td>[41 51]</td>
<td>[11 26]</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>[25 50]</td>
<td>[51 101]</td>
<td>[26 51]</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>[50 75]</td>
<td>[101 201]</td>
<td>[51 101]</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>[75 100]</td>
<td>[201 301]</td>
<td>[101 151]</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>[100 150]</td>
<td>[301 401]</td>
<td>[151 201]</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>[150 300]</td>
<td>[401 501]</td>
<td>[201 251]</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>[300 1000]</td>
<td>[501 601]</td>
<td>[251 501]</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>[1000 2000]</td>
<td>[601 701]</td>
<td>[501 1001]</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>≥2000</td>
<td>≥701</td>
<td>≥1001</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

*For the population density, the classes and their corresponding (transformed) values into [0 1] are adapted from Contreras (2007).

Table 4(a) summarizes a dataset of nine water mains and illustrates the clustering process. For each water main, five attributes were collected as shown in Table 4(a), which are Pipe ID (pipe identifier), Age (pipe age in year), Diameter (pipe nominal diameter in mm), Length (pipe length in meter), and number of pipe breaks (BK) recorded during the monitoring period. First, the water mains are grouped into three classes based on their diameter (D) as shown in Table 4(b). These classes are C1 (D ≤ 50 mm), C2 (50 < D ≤ 90 mm), and C3 (D > 90 mm). Thereafter, the water mains in each class of diameter are grouped into n classes based on their length. However, this second clustering is not relevant because there are only three water mains per class. Then for each class of water mains the class equivalent age and diameter are computed using Equation (2). Thereafter, the total length and number of breaks as well as the number of breaks per year and per kilometer of pipe (#/year/km) per class are calculated as shown Table 4(b).

The breakage rates predicted by Equation (1) (for City of Kelowna water mains) are transformed on a scale between zero and one. Then these normalized values are distributed into three linguistic grades: low (Str.FI < 0.1), medium (0.1 ≤ Str.FI < 1) and high (Str.FI = 1) using two threshold values. All the threshold values used in the WARRM can be fine-tuned to meet the stakeholders’ need.

**Soil corrosiveness index**

SCI is measured using a point scoring method with different assumptions for metallic, cementitious, and plastic pipes. There are many point scoring methods such as the 10-point, 12-point, 25-point, and other scoring methods. The 10-point scoring method is commonly used to determine soil corrosiveness for metallic pipes (Najjaran et al. 2003; Sadiq et al. 2005). This method was introduced by the Cast Iron Pipe Research Association and recommended by the American Water Work Association (AWWA 1999). It considers soil properties such as resistivity, pH, redox potential, and sulfide and moisture contents. A score is assigned to each soil property as shown in Table 5 for a particular soil sample and the points are summed. The soil is considered as corrosive if the sum is greater than 10, otherwise it is considered as non-corrosive (Sadiq et al. 2005; Liu et al. 2010). However, previous studies showed that this method wrongly identifies some non-corrosive conditions. Based on the work carried out by Doyle (2000) related to this uncertainty and the authors’ experience, three corrosiveness classes were
defined, which are low (<4.5 points), medium (4.5–13 points), and high (>13 points).

For concrete and asbestos-cement (AC) pipes (i.e., cementitious), AWWA (2003) provided information about the soil pH for non-sulfate acidic soils below which AC pipes will be attacked. Hu et al. (2008) proposed the sulfate aggressiveness classification for soluble sulfates in soil at neutral or basic pH. The soil corrosiveness is low if the total point score of the three properties (pH, clay percentage, and sulfide content) is <2, medium for a score between 2 and 6, and high otherwise. Since usually the type of AC pipes is not defined and information about sulfate is unavailable, soil sulfide content was thus considered (Table 5).

Table 3b | Preference weights used in the risk index model

<table>
<thead>
<tr>
<th>Level 5</th>
<th>Level 4</th>
<th>Level 3</th>
<th>Level 2</th>
<th>Level 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>Weight</td>
<td>Factor</td>
<td>Weight</td>
<td>Factor</td>
</tr>
<tr>
<td>Regression model used (Diverse parameters)</td>
<td>Structural Failure Index (Str. FI)</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point scoring model used (Diverse soil parameters)</td>
<td>Soil Corrosiveness Index (SCI)</td>
<td>0.30</td>
<td>Structural Integrity Index (SII)</td>
<td>0.6</td>
</tr>
<tr>
<td>pH(^a)</td>
<td>0.5</td>
<td>Aggressiveness Index (AI)</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Free residual chlorine(^a)</td>
<td>0.5</td>
<td>Pressure</td>
<td>0.8</td>
<td>Hydraulic Capacity Index (HCI)</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.2</td>
<td>Land use</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Population density</td>
<td>0.35</td>
<td>Pipe diameter</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Pipe length</td>
<td>0.1</td>
<td>Turbidity</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Color</td>
<td>0.04</td>
<td>Free residual chlorine</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Water age</td>
<td>0.13</td>
<td>Water velocity</td>
<td>0.09</td>
<td>Water Quality Index (WQI)(^b)</td>
</tr>
</tbody>
</table>

\(^a\)Valid for metallic pipes.

\(^b\)The WQI is associated at Level-1 to the RI for improving the risk management.
For plastic pipes, there is no specific guideline to assess the external soil effects. Backfill materials, potentially harmful to bed soil (e.g., rock soil, gravel), are the main concern. Based on literature review, a simple scoring system inspired from the 10-point scoring method (AWWA 1999) and based on clay and gravel percentages has been proposed to estimate the soil effects on plastic pipes as seen in Table 5. The soil corrosiveness is low for a score <3, medium if the score is between 3 and 6, and otherwise high. Finally, the scores are transformed into index values (SCI) on the scale between zero and one.

**Aggressiveness index**

The water carried by a pipe may have negative impacts such as leaching and internal corrosion on metallic and cementitious pipes. The AI for plastic pipes is ignored because the water aggressiveness would have an impact on these pipes only after a long time. For cementitious pipes, Hu & Hubble (2007) developed a function shown in Equation (3) to estimate AI based on water pH, total alkalinity A (mg/L CaCO₃), and calcium hardness H (mg/L CaCO₃). The water carried by a cementitious pipe is considered very aggressive if \( \frac{AI}{C_{20}} \geq 10 \), moderately aggressive if \( 10 > \frac{AI}{C_{20}} > 12 \), and otherwise non-aggressive. Finally, the AI for cementitious pipe is transformed into values comprised between zero and one (\( [0, 1] \)).

\[
AI_{\text{cementitious}} = \text{pH} + \log[AH]
\]  

**Water quality index**

WQI will be associated to the final RI for each pipe to favor appropriate recommendations because water quality failure does not necessarily mean water main failure. Poor water quality could result from various other causes such as inadequate or insufficient treatment, inadequate flushing frequency, booster non-optimized location and/or chlorine dosage (Kirmeyer et al. 2001; WHO 2004; NRC 2006; Sadiq et al. 2007). WQI is determined based on input parameters such as turbidity, color, velocity, water age, and FRC. For aggregating all these attributes and estimating the WQI, sub-index values were derived from their monitored or simulated values using appropriate transformation functions and weights \( w(.) \) assigned to them. Equation (4) shows the aggregation process for a given vector of water attributes. The WQI values were grouped into low (WQI \( \leq 0.49 \)), medium (0.5 \( \leq \text{WQI} \leq 0.74 \)), and high (WQI \( \geq 0.75 \)).

\[
WQ = w_T \times T_{SI} + w_C \times C_{SI} + w_{FRC} \times FRC_{SI} + w_{WA} \\
\times W_{AS} + w_V \times V_{SI}
\]
where $T_{SI}$, $C_{SI}$, $FRC_{SI}$, $WA_{SI}$, and $V_{SI}$ are the sub-index (transformed) values derived from turbidity, color, FRC, age, and water velocity values, respectively.

### Hydraulic capacity index

HCI is estimated by aggregating water pressure ($P$) and velocity ($V$). Water pressure and velocity values were converted into sub-index ($P_{avgSI}$ and $V_{avgSI}$) values belonging to [0 1] to allow their aggregation since they are non-commensurate factors. A preference weight ($w$) is assigned to each of them and HCI is estimated using a weighted average as shown by Equation (5). The obtained HCI values were grouped into low ($HCI < 0.26$), medium ($0.26 \leq HCI < 0.75$), and high ($HCI \geq 0.75$)

$$ HCI = w_P \times P_{avgSI} + w_V \times V_{avgSI} $$

### Structural integrity index

SII of a pipe is derived by aggregating its Str.FI, the SCI, and water AI as shown in Equation (6). The coefficients $w_{Str.FI}$, $w_{SCI}$, and $w_{AI}$ are the weights assigned to SII, Str.FI and SCI, respectively. These weights may be changed by the users. The SII values were then classified into three classes: low ($SII < 0.15$), medium ($0.15 \leq SII < 0.57$)
The obtained VI values were grouped into low (VI < 0.26), medium (0.26 ≤ VI < 0.50) and high (VI ≥ 0.50)

\[ VI = w_{SII} \times SII + w_{HCI} \times HCI \]  \hspace{1cm} (7)

**Consequence index**

CI is determined through aggregation of input factors such as LU, population density (PD), pipe diameter (D) and pipe length (L) using a weighted average as shown in Equation (8). The coefficients \( w_{LU}, w_{PD}, w_{D}, \) and \( w_{L} \) are the weights assigned to LU, PD, D and L, respectively. These weights are user defined and their sum is equal to one. The CI final results were grouped into low (CI < 0.35), medium (0.35 ≤ CI < 0.52), and high (CI: ≥ 0.52)

\[ CI = w_{LU}LU + w_{PD}PD + w_{D}D + w_{L}L \]  \hspace{1cm} (8)

**Risk index**

RI is estimated from VI and CI using a weighted average as shown in Equation (9). The coefficients \( w_{VI} \) and \( w_{CI} \) are the weights assigned to VI and CI, respectively. These weights are user defined and their sum is equal to one. The index values ranges between 0 (i.e., good) and 1 (i.e., bad). The RI values are categorized into low (RI < 0.30), medium (0.30 ≤ RI < 0.45) and high (RI ≥ 0.45) risk

\[ RI = w_{VI}VI + w_{CI}CI \]  \hspace{1cm} (9)

**Risk management**

In the RM part, recommendations such as maintenance or repair or replacement after inspection (i.e., M/R/R) are provided based on the RI and WQI outcomes. Note that water quality deterioration does not necessarily have direct implication on the decision-making process for a water main replacement. This WQI is proposed as a complement for improving the overall decision-making process and network performance. Therefore, nine recommendations were defined using a rule-based decision matrix as shown in Table 6 to improve the overall performance of the network.
The rules are defined based on the risk and water quality failure indices.

Customizing the general framework for specific water main material

A WSN may comprise different pipe materials that determine significantly the modes of failure. Thus the general framework is customized according to three types of pipe materials (i.e., metallic, cementitious, and plastic). For the metallic pipes, the general framework is used without including alkalinity and hardness to determine AI, and percentages of fines and gravel to determine SCI. For the cementitious pipes, the general framework is used without including soil pH, Redox potential, sulfides to determine SCI, and without FRC to determine AI. For the plastic pipes, the general framework is used without including AI since the carried water has no significant impact on these pipes based on current knowledge. Moreover, SCI is determined by considering only the percentages of fines and gravel.

DESCRIPTION OF THE CASE STUDY AREA

The WSN of the City of Kelowna in British Columbia (Canada) was used to demonstrate the proposed approach. This network serves more than 50,000 residential consumers and 1,700 industrial, commercial, and institutional properties (City of Kelowna 2012). Raw water is abstracted from the Okanagan Lake through three intakes and it is disinfected by chlorination and UV in some cases. Parameters such as FRC, turbidity, and color are routinely monitored in more than 60 locations. Alkalinity, pH, and hardness are monitored in three pumping stations. The water quality database used for illustrating the proposed approach covers seven years (2005–2011) of data. These data were divided into summer (May to October) and winter (November to April) because the tremendous seasonal variations recorded in similar regions play an important role on network operation and maintenance, water quality, and consumer perceptions (Francisque et al. 2009a, b; Montenegro-Rousseau et al. 2009).

For water main inventory, two databases were obtained from City of Kelowna. The first database, henceforth referred to as ‘as built’, provides basic pipe characteristics of the 2,598 water mains. The second database, henceforth referred as DB2, is derived from an EPANET hydraulic model that is used for decision-making by City of Kelowna. There was a huge discrepancy between the numbers of pipes and the unique identifiers (ID) of these two databases. Therefore, an intensive ID matching was done to combine the information of the two databases into one database to conduct this study. The combined database provides information on 2,598 pipes of various materials, age, and particularly diameters summarized in Table 7. It shows that plastic pipes, which include polyvinyl chloride (PVC) and high-density polyethylene (HDPE), cementitious (AC and concrete), and metallic (cast iron, ductile iron, copper, steel, and

<table>
<thead>
<tr>
<th>Pipe characteristics</th>
<th>Cementitious pipes</th>
<th>Metallic pipes</th>
<th>Plastic pipes (PVC - HDPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AC</td>
<td>Concrete</td>
<td>CI</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>100–500</td>
<td>500–900</td>
<td>100–400</td>
</tr>
<tr>
<td>Length (m)</td>
<td>0.15–1198</td>
<td></td>
<td>12–1204</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>168,302</td>
<td></td>
<td>47,717</td>
</tr>
<tr>
<td>Total no. of pipes</td>
<td>849</td>
<td>33</td>
<td>286</td>
</tr>
<tr>
<td>Total no. of breaks</td>
<td>141</td>
<td></td>
<td>57</td>
</tr>
<tr>
<td>Total no. of broken pipes</td>
<td>106</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>First break record obtained in the year</td>
<td>1976</td>
<td></td>
<td>1977</td>
</tr>
<tr>
<td>Percent (%) of pipes broken</td>
<td>12%</td>
<td></td>
<td>12.6%</td>
</tr>
</tbody>
</table>
Figure 3 | Distribution of the values of the indices for City of Kelowna WSN (summer 2011) apportioned into three classes, low, medium, and high: (a) structural failure, soil corrosiveness, and carried water aggressiveness indices; (b) SII; (c) hydraulic capacity (failure) index; (d) VI; (e) consequences indices; (f) risk index; and (g) WQI.
Figure 4 | Spatial distribution of three indices for City of Kelowna water mains (summer 2011): (a) VI; (b) CI; and (c) RI.
galvanized) pipes represent 55, 34 and 11% of the total pipes, respectively. The percentage of pipes broken is relatively low especially for plastic pipes (<1%). It is interesting to note that some attribute data (e.g., material, diameter, and break rate) and hydraulic information for some water mains were missing. They were not collected or could not be matched with the ‘as built’ database due to lack of resources (City of Kelowna 2012).

RESULTS AND DISCUSSION

For prioritizing City of Kelowna water mains for M/R/R, a risk-based prioritization tool is developed using Excel macro programming. This tool combines the likelihood of failure (vulnerability) of each water main and the associated consequences in order to identify the risk of water main failure. This tool can help the utility managers to make reasonable decisions based on a better understanding and knowledge of the network structural failure, soil corrosiveness, water aggressiveness structural integrity, hydraulic capacity, likelihood of failure (vulnerability), associated consequences, and the overall risk of failure assessed in terms of indices. The following subsections provide the results obtained for each index and suggest RM options.

Figure 3(a) shows the Str.FI, SCI, and water AI results for City of Kelowna. The Str.FI results show that around 95% of the water mains have an acceptable condition, as 65 and 30% of the water mains have low (very good) and medium structural failure conditions, respectively. Few water mains...
appear to be in high structural failure condition needing special attention from the utility manager and maybe immediate action to prevent their failure. These results can be attributed to the fact that most of the water mains are plastic pipes as previously discussed. These pipes are relatively young and characterized by very much lower breakage occurrence.

The soil corrosiveness index results (Figure 3(a)) show that 95% of the water mains are subjected to an acceptable soil corrosiveness condition. For 45 and 50% of the water mains, the soil corrosiveness index is low (very good) and medium (acceptable), respectively. The SCI index is high for about 5% of the water mains; these might need frequent inspection to avoid their failure due to corrosion. Analysis of this result reveals that all the water mains subject to a high level of soil corrosiveness are metallic and AC pipes and they are located in the north-eastern part of the network. Further investigation shows that this area is characterized by low resistivity and redox potential and a high level of sulfide content detrimental for metallic pipes. For AC pipes, pH and sulfide content are high.

The AI results show that more than half of the water mains are not impacted by the carried water aggressiveness since they are plastic pipes. Almost half (44%) of the water mains are subject to an acceptable level of water aggressiveness, as 4 and 40% of the water mains are under low and medium water aggressiveness, respectively. None of the water mains is under high aggressiveness from the potable water. However, AI was not assessed for 1% of the water mains since data (e.g., pipe material) are not available.

The SII results are shown in Figure 3(b). This figure indicates that almost 94% of the water mains have an acceptable level of structural integrity (SII <0.57), because 41 and 55% of the water mains have low and medium SII, respectively. Few water mains have a bad structural integrity level (SII ≥0.57) and for these the utility managers should take a proactive measure in order to avoid their (structural integrity) failure.

The HCI results are presented in Figure 3(c). It shows that more than 80% of the water mains have acceptable hydraulic capacity, as over 70 and 10% of the water mains are subjected to low (very good) and medium hydraulic capacity failure conditions. Very few water mains (<2%) have a high (bad) hydraulic capacity failure which requires special attention from the utility manager. However, HCI was not estimated for around 16% of the water mains that
are not connected to the main network or matched with any pipe of the available hydraulic model. The HCI results of these water mains are presented as input missing.

The VI results are presented in Figure 3(d). It shows that almost 72 and 25% of the water mains have low (very good) and medium VI, respectively. Few water mains (i.e., around 3%) are highly vulnerable. These high vulnerable water mains require proactive inspection and measures to prevent their failure. The VI values were mapped (see Figure 4(a)) using GIS software to have a better spatial insight and help utility managers to carry out appropriate intervention. This map shows that there is no particular pattern to the spatial distribution of the water mains based on their vulnerability. However, the most vulnerable water mains are concentrated at the north-east and south-west parts of the network. These water mains must be investigated by the utility managers to extract useful information that can help decision-making.

The CI results are displayed in Figure 3(e). This figure shows that in case of failure the associated consequences are medium (acceptable) for 83% of the water mains. Few water mains have low consequence of failure and around 10% of the water mains will lead to high consequences in case of failure. The utility managers must give special attention to those water mains for which the consequences of failure are high and take proactive actions to prevent their
failure. For very few water mains CI was not estimated due to missing values (e.g., pipe material, or diameter). The CI values were also mapped (see Figure 4(b)) using the GIS software to have a better spatial insight and help utility managers to carry out appropriate intervention. This map shows that most of the water mains located at the northern part of the network have a high CI in case of failure, whereas most of the water mains located in the southern part have a low or medium CI in case of failure.

The RI results, its map, and the ranking of the water mains based on RI are presented in Figure 3(f), Figure 4(c), and Figure 5, respectively. Figure 3(f) shows that globally the network is not at risk because almost 65 and 30% of the water mains record low (very good) and medium RI values, respectively. That means almost 95% of the water mains exhibit an acceptable risk level and the remaining water mains (around 6%) are at high risk. For those water mains at high risk, the utility managers must conduct proactive inspections and take measures (e.g., maintenance, rehabilitation, or replacement) to prevent their failure. The RI values were mapped as shown in Figure 4(c) using the GIS software to have a better spatial insight and help utility managers to carry out appropriate intervention. This map indicates that there are two hotspots for risk of failure. These hotspots are located at the north-east and south-west parts of the network. Figure 5 presents the rank of the water mains from high risk to low risk. This figure reveals that metallic water mains fall in the high risk rank, whereas PVC water mains fall in the low risk rank.

The WQI results are shown in Figure 5(g). This figure shows that 77% of the water mains have low WQI (i.e., good water quality) and 6% of the water mains have medium water quality conditions. These results indicate that most of the water mains carry an acceptable water quality. For any of the water mains, the WQI is high. However, it is worth noting that the water quality condition for 17% of the water mains was not assessed due to missing data.

RM results are presented at the last column of Figure 5. This figure shows various recommendations (i.e., maintenance, repair or replacement) provided for each water main based on the RI first, which thereafter is associated with the WQI values using the rule matrix (Table 6) previously described. For instance, a recommendation to ‘Increase inspection and decide for replacement/rehabilitation’ was provided for the first water main (ID: 125654) based on high (H) RI and low (L) WQI values. On the other hand, a recommendation to ‘Do nothing’ was provided for the last water main (ID: 125843) based on low (L) RI and WQI values.

The WARRM developed is used by the managers of the City of Kelowna WSN as a planning tool. The interface of
the tool created using Microsoft Visual Basic software is very straightforward. From the Welcome page, as shown by Figure 6(a), the user has the choice to consider, for example, the indices for each single water main (Individual Pipe tab) or for the overall network (Overall System tab); she/he can add new data and recalibrate the model (Model Calibration tab). The user can also look for help from this page by selecting the Help tab that will prompt her/him to the User Manual, a portable document file (PDF) associated with the tool (Figure 6(b)).

When the user selects the Individual Pipe tab, the tool prompts her/him to a window showing all information for a given water main, in particular the indices as well as the appropriate recommendation related to the RI value (Figure 7). The user can select the water main she/he wants to observe through the dropdown list arrow beside the pipe ID. The graphs for the given pipe can be shown by clicking on the Graphs tab. For the Overall System some of the results prompted by the tool have been previously shown (Figures 3 to 5).

To add new data, the user will select the New data tab that will return a window with a tab for each type of data involved in the model, as shown by Figure 8. The indices for each water main for which new data have been added, related information (graphs, recommendation, etc.) and subsequently those for the overall system will be automatically updated. However, if the new data are related to the water main breakage predictions (Str.FI) the user must recalibrate the model by selecting the Model Calibration tab after entering these new data.

**SUMMARY AND CONCLUSIONS**

A risk-based decision-making tool, named WARRM was developed to prioritize recommendations for water mains such as M/R/R for small to medium sized water distribution networks. The developed tool is then illustrated using the City of Kelowna water distribution network as a case study. The necessary data related to the network were provided by the utility or gathered from various sources including the environmental parameters. The results for the case study show that most of the water mains are in an acceptable condition. Few water mains showed a high level of structural failure potential. These water mains are subjected to a high level of soil corrosiveness and water aggressiveness. They showed they have a high likelihood of failure (or vulnerability) since they are subjected to a high level of structural integrity and hydraulic capacity failures. Most of the water mains showed they have low risk of failure while a few of them showed they are at high risk of failure. To manage the risk some recommendations (i.e., maintenance, repair or replacement, etc.) have been suggested to the managers of the WSN as stated earlier.

In general, the developed tool demonstrated that it can allow utility managers to optimally plan their interventions and allocate limited resources. However, this tool does not fit all cases. It is specific to the City of Kelowna WSN for which it has been built. Nevertheless, the approach developed in this research can be used by any type of WSN, in particular the small to medium sized ones provided the specific data of the given WSN used to feed the model. More importantly, the model to identify the network historical patterns of pipe breakage rates and thereafter to use for predicting water main breaks must be one specifically developed for the given WSN using, among others, its own water main characteristics, historical and environmental data.

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