Water mains renewal planning framework for small to medium sized water utilities: a life cycle cost analysis approach

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ABSTRACT
For the last few decades, concerns have repeatedly been raised about deteriorating water mains in Canada. Small to medium sized water utilities are generally impacted more due to lack of technical and financial resources. This paper presents a user-friendly life cycle cost (LCC) analysis-based decision support tool to help these utility managers to prioritize water mains rehabilitation or replacement (R/R) strategies. The deterioration curves for water mains of different materials and sizes have been developed based on their likelihood of failure. The proposed model is implemented for the water supply network of City of Kelowna (Canada). It compares the costs of various R/R scenarios for each pipe over its life cycle and suggests the most cost-effective decision to the managers to efficiently allocate their limited resources.

1. Introduction
Canadian municipalities are facing increasing challenges with their aging water supply infrastructures. Most of these municipal infrastructures have reached the end of their design life, as they were installed between 1950 and 1970 (Mirza 2007). According to the 2012 Canadian Infrastructure Report Card, two decades of declining public investment in infrastructure has exacerbated the challenge (CCA et al. 2012). This led to the deferral of crucial investment in infrastructures resulting in their physical decline. In terms of drinking water infrastructure replacement, $2.59 billion is estimated for replacing the infrastructures in “fair”, “poor”, and “very poor” conditions (CCA et al. 2012). This gap will impact mostly small to medium sized water utilities due to lack of human and financial resources (Francisque et al. 2014, Haider et al. 2014). Therefore, it is crucial for the managers of such water utilities to effectively prioritize the required interventions, and optimally allocate their limited human and financial resources.

Imran et al. (2007) defined the water supply infrastructure integrity as its ability to transport water in adequate quantity, acceptable quality, and with minimal interruption. Water mains failures can be identified by increasing pipe breakage rate, decreasing hydraulic capacity, and continuously degraded water quality (Lounis et al. 2010). Failures of water mains may cause significant health and socio-economic impacts that may adversely affect public confidence (Pelletier et al. 2003). The socio-economic consequences include (not limited to) loss of treated water, flooding of streets and sometimes homes, contaminant intrusion into the distribution network, loss of business, and costs associated with emergency response (Kirmeyer et al. 2001). The primary objective of a water utility is to operate these valuable assets efficiently throughout their lifecycle. Therefore, prioritizing water mains for rehabilitation and/or replacement (R/R) actions requires not only physical and water quality considerations, but also那些 related to the cost of these improvement actions over the entire life cycle of pipes.

Life cycle cost (LCC) of an asset is the total cost over its life span including planning, design, acquisition and support costs and any other costs directly attributable to owning or using the asset (Ammar et al. 2012, Rajani and Kleiner 2004). Life cycle cost analysis (LCCA) efficiently evaluates the investment options by taking into account all aspects of lifetime cost of the system such as agency costs and the impacts of the system on the users in particular and on the society in general (Kleiner et al. 2001, Engelhardt et al. 2003, Shahata and Zayed 2013). The main motivation for using the LCCA approach is to optimize the operation and maintenance costs (e.g., mains flushing, handling of complaints, mains repair or replacement) during the operational phase (Engelhardt et al. 2003, Lim et al. 2006, Shahata 2006).

Most of the previous LCC studies mainly focused on larger utilities where a large number of pipe failure data and a sufficient number of experts are available (Engelhardt et al. 2003, Kleiner et al. 2001, Lim et al. 2006, Shahata 2006, Shahata and Zayed 2013). The amount of water main break data needed for those extensive model developments is not commonly available in smaller utilities (Kabir et al. 2015, Wood and Lence 2009). Most of the small to medium sized utilities do have some basic information on their
2. Methodology

2.1. Proposed framework

The LCC based framework developed in this study for water mains renewal of small to medium sized utilities is shown in Figure 1. The proposed framework capitalizes on the vulnerability index (VI) of water mains to estimate their deterioration over time. Subsequently, their remaining service life (RSL) and the related costs of the R/R actions are estimated to maintain a minimum acceptable level of service (MALOS). In this study, the MALOS is defined as the lowest level of service (LoS) that can be set by the water utility managers to satisfy their customers. LoS varies from ‘Excellent’ to ‘Very bad’ and is derived from the network vulnerability index. The WARRM will be used to prioritize the strategies for water main R/R over time. The tool is integrated with a geographic information system (GIS) to combine the non-spatial and the geographic (spatial) attributes of water mains. The use of GIS improves the visualization (mapping) and spatial analysis for more informed decision-making.

2.2. Life cycle cost analysis approach

WARRM accommodates the deterioration profile and the remaining service life prediction (SLP) of the water mains in a status quo situation as well as various rehabilitation scenarios for extending their SLP. The model includes the analysis of the costs of this extension by comparing them to the costs of the replacement scenario at the time of each rehabilitation action. The main components of the model are described in the following sections.

2.2.1. Water mains deterioration curves

The deterioration curves for water mains of different materials and sizes have been developed based on their VI, or likelihood of failure. This index is derived from (i) the hydraulic capacity index (HCI), which involves the water average pressure (P) and velocity (V), and (ii) the structural integrity index (SII) (Figure 1).

SII is obtained from the aggregation of the water aggressiveness (AI), soil corrosiveness (SCI), and water mains structural failure (Str.FI) indices. The Str.FI is a statistical model used to understand the patterns of historical pipe breakage rates for the water mains of the utility under study and to forecast the future water main structural deterioration (breaks). Estimation of Str.FI involves pipe diameter (D), length (L), and age (A), it is the only index that significantly varies over time with the pipe age. A unique model is developed for each type of pipe material (i.e., metallic pipes, plastic pipes, and cementitious pipes) inventoried in the WSN of the utility.

Certainly, the deterioration curves vary according to the pipe material and, for a given pipe material, the pipe diameter, as stated in literature (e.g., Berardi et al. 2008, Giustolisi et al. 2007). However, the principle used in this study for forecasting the pipe deterioration over time is identical in all models. For each pipe size (e.g., $D = 100$ mm) of a given material (e.g., cast iron), at least, the next 50 years starting from the year 2013 are considered and added to the present pipe age with a time step of one year. Thereafter, Str.FI of the pipe is computed for each of the next 50 years, i.e., for 2013, 2014, and so on, and combined with SCI to obtain its SII. Figure 1 shows that in case of metallic or cementitious pipes, the water AI is also used, because it is well known that it has an impact in the deterioration of those pipe materials (e.g., Francisque et al. 2014, Tamminen and Ramos 2008, Yamini and Lence 2010). Then SII is combined with HCI to obtain a new VI for each of the next 50 years. For detailed information about the input factors involved in each index, aggregation process to develop the indices and how the latter are combined to ultimately assess the structural integrity, the consequence, and
subsequently the risk of failure indices, readers are referred to Francisque et al. (2014). Subsequently, for each group of pipes based on the material and size (e.g., cast iron pipes of diameter of 100 mm), the medians of these VI values (more than 50 for each group of pipes) are fitted over an exponential function where VI is the dependent variable and pipe age is the predictor. Microsoft Excel tool Solver is used to optimizing the values of the coefficients “α” and “β” of the exponential function by minimizing the square root of the mean square error (SRMSE) between the predicted and observed VI values. The general form of the fitted function is given in Equation (1).

\[ VI = ae^{\beta \times \text{Age}} \]  

(1)

Due to the uncertainty involved in Equation (1), a confidence interval has been defined based on the concept of standard error. A twenty percent increase or decrease of VI has been considered respectively for the upper and lower bounds. Since VI varies between 0 (good) and 1 (bad), the upper bound of the interval represents the low confidence limit, and the lower bound the high confidence limit. This confidence interval will guide the decision makers (water utility managers) to assess the most likely instant (pipe age) to take action: if their level of confidence about the VI estimation is low, they should intervene earlier, conversely, they should act later in the case of high confidence level. The values of VI computed by the model are done for an average level of confidence. Once, based on Equation (1), the deterioration profile/curve of each group of mains is defined, its service life can be predicted.

2.2.2. Service life prediction

In general, the RSL of a structure is a time period at the end of which the structure stops performing the functions it was designed and built for (Li and Mahmoodian 2013). The deterioration curves developed in the present study provide an overview of the RSL of each group of pipes. Theoretically, when the vulnerability index of a water main approaches to its maximum value of “1”, it can be assumed that the main has now reached to its worst condition and should be replaced. The age of the pipe can be estimated at this point (i.e., VI = 1) from Equation (1) or graphically from its deterioration curve. Adding this value (the number of years), for example, 80 years, to the pipe installation year, for example, 1980, will provide the year, i.e., on 2060, to replace the pipe. This is a “Do nothing” situation.

LoS describes the quality of service provided by the water mains to the customer, it varies from ‘Excellent’ to ‘Very bad’. The WSN manager can establish a minimum acceptable LoS (derived from the VI values) to satisfy the consumer. Based on this LoS, the utility can determine whether or not it is meeting customer expectations and its statutory obligations to deliver the required services (Infrastructure Canada 2002). An appropriate rehabilitation intervention (action) should be performed on the water main each time the minimum acceptable LoS will be reached. The impact of the rehabilitation action on the pipe vulnerability (i.e., the decrease of the pipe vulnerability which means an increase of the LoS), must be estimated by the manager. In result, the RSL of the water main will be extended for a certain number of years, which can also be estimated from the new SLP curve. The manager can set the minimum acceptable LoS (e.g., Good) based on a certain range of VI values corresponding to a given pipe breakage rate (# breaks/year/km). Furthermore, various rehabilitation scenarios can be compared to a replacement action to evaluate their impacts on the RSL of the pipe. Finally, their cost analysis can be carried out to select the best action.

2.2.3. Life cycle cost (LCC) analysis

As shown in Figure 1, the LCC analysis is the next step after predicting the RSL of the main. Over time, water mains become overstressed and may fail before the end of their design lives, therefore, it is important to consider the LCC, particularly the residual life of the water mains in rehabilitation/replacement (R/R) planning. The most commonly used LCC method is the present value (PV) method (Rajani and Kleiner 2004). The PV is estimated for the future by accounting for the anticipated inflation of present worth (dollars) and discounting that amount by a predicted rate, over the period of the anticipated time of the future expenses and the present time (Rahman and Vanier 2004). Two main methods, deterministic and probabilistic, are used in LCC modeling. In this research, a modified deterministic model is used for simplicity and to deal with data limitations in small to medium sized utilities.

In the deterministic method, a discounted rate is used to compare all costs in the present value (NSWT 2004, Rahman and Vanier 2004). All the cost components of a project are assumed to be well defined with a single value based on the economic analysis of time-value (Shahata 2006) and are identified by the year with certainty. In order to find the total LCC of a project, the present values of each type of cost must be summed, whereas any kind of positive cash flows, such as a resale value, must be subtracted (Boussabaine and Kirkham 2004). The present value of the total LCC can be assessed from Equation (2) (Rahman and Vanier 2004) as:

\[ LCC = C_p + \sum_{i=1}^{n} \frac{C_i}{(1+i)^t} \]  

(2)

where, \( C_p \) is the capital cost, \( C_i \) is the sum of operation, repair/rehabilitation/replacement costs and salvage value, \( i \) is the discounted rate, and \( n \) is the asset service life.

Capital costs of a project are all costs incurred for the project until it is operational, i.e., for the first four out of six sequential steps illustrated by Boussabaine and Kirkham (2004). They include costs related to (i) the Justification for investment and customer’s requirements (if any), (ii) the Conceptual development, (iii) the Design stage, and (iv) the Production stage. In the case of the water mains of a water supply network, the costs for buying and installing pipes are capital costs. Therefore, in this research, the capital costs will not be considered in the rehabilitation scenarios (operational stage). The capital costs will be used in the pipe replacement scenarios as well as the expected operational costs for pipe break repairs over time provided that the new pipe is installed. An asset salvage value is its expected value at the end of its service life which is assumed to be zero in this study.

Life cycle cost profile development involves the following three steps:

Step 1: the estimation of the time of future activities,
Step 2: the identification of R/R scenarios, and
Step 3: the estimation of the maintenance, repair, rehabilitation, and replacement costs.
As stated earlier, the future deterioration of the water main can be assessed by an exponential function presented in Equation (1). If a MALoS, corresponding to a certain value of the network water main VI, is established, Equation (1) allows the utility managers to estimate the time for future activities. The second step refers to the determination of the SLP of the water mains as described above. Provided that an efficient and feasible rehabilitation technology exists, each rehabilitation action will increase the RSL of the water mains. In parallel, the replacement of water main should also be evaluated as a scenario. Finally, for the third step, the costs of each water main break repair, rehabilitation scenario (e.g., lining, wrapping/coating, cathodic protection, lining and cathodic protection, etc.), and replacement scenario must be obtained from the network manager.

3. Case study - the city of Kelowna

3.1. Study area

In order to demonstrate the applicability of the proposed approach, WARRM was applied on a medium sized WSN (City of Kelowna, British Columbia (BC), Canada). The WSN of the City of Kelowna consists of 2598 water mains of various materials. i.e., cast iron (CI), ductile iron (DI), steel, galvanized (Galv), copper (Cop), PVC (Polyvinyl Chloride), HDPE (High-Density Poly Ethylene), asbestos-cement (AC), and concrete (Conc) pipes. The database obtained from the utility shows that the contribution of metallic, cementitious, and plastic pipes are 11%, 34%, and 55% respectively. For the metallic pipes, particularly the CI and DI pipes, the diameters vary from 100 mm to 400 mm and from 25 mm to 1350 mm respectively. These pipes were installed between the years 1939 and 2009. The diameters of the plastic pipes go from 50 mm to 750 mm while their installation year varies from 1963 to 2010. For the cementitious pipes, the diameters of the AC and concrete pipes are between 100 mm and 500 mm and 500 mm and 900 mm respectively. The oldest of these pipes was installed in 1939 whereas the youngest in 2010. For further details on the WSN of the City of Kelowna database used, and estimation of indices, interested users should consult Francisque et al. (2014).

3.2. Results and discussion

3.2.1. Water main deterioration curves

The deterioration curves have been developed for each pipe size and material. These essentially are the curves of VI values over time of each group of mains based on the material and diameter size (e.g., cast iron of 100 mm) as per Equation (1). Fifty-one groups of pipes have been defined and, therefore, all the results cannot be provided due to space limitations. The discussions are limited to two selected examples of small and large diameter CI water mains. However, Table 1 provides the values of the parameters “α” and “β” for the deterioration curves of all the 51 pipe groups. A more detailed overview of the model is attached in Appendix A.

Seven sizes of CI water mains are inventoried for the City of Kelowna WSN (i.e., 100 mm, 150 mm, 200 mm, 250 mm, 300 mm, 350 mm, and 400 mm). However, only the results for the smallest (100 mm) and the largest (400 mm) CI pipes are discussed here. This is due to the fact that among others the two groups of pipes might represent the two extreme cases, knowing that the pipe diameter has an impact on its breakage rate as stated earlier. Figure 2 shows the fitted deterioration curves (blue curve) as well as the curves corresponding to the low (red) and high (green) confidence levels situations to estimate the VI. For all sizes and materials, initially, the pipe deterioration is slow and then increases gradually with time. However, the initial VI values and the slopes of the curves vary widely for different groups. This provides, for a given threshold value (corresponding to a certain LoS), a different age at which the manager should take R/R actions for each pipe size and material. The age of a pipe group for the VI threshold value is calculated from Equation (1) and then added to the installation year of each pipe of the group to estimate when (i.e., which year) the improvement action should be taken. Based on Equation (1) (or graphically from the pipe deterioration curve) if it appears, for example, for a given VI threshold value, that R/R actions should be taken for a pipe when the latter will be 90 years old. If this pipe was installed in 1954 for example, this action should then be taken in the year 2044 (i.e., 1954 + 90).

Figures 2a and 2b highlight that the age of the smallest (100 mm) CI water mains, when the manager should take R/R action, is higher in comparison to the age of the largest CI (diameter of 400 mm) for similar action. For instance, if the manager sets a minimum VI value of 0.5, R/R action should be required at a more advanced age for the smallest CI water mains than for the largest. The difference is of at least seven years later for the smallest pipes (100 mm). This could be perceived as not in conformity with models previously developed by some authors (e.g., Berardi et al. 2008, Giustolisi et al. 2007) suggesting an inverse relationship between pipe diameter and breakage rate. However, in these models, only the pipe breakage rate was considered whereas the pipe VI used in this study has broader meanings. In addition to the pipe breakage rate, the VI includes its HCI as well as the SCI, and water AI indices. These variables may just sometimes hide the relationship suggested by these authors.

3.2.2. Service life prediction

To assess the RSL of each pipe group (and its extension through rehabilitation actions), the utility manager also needs to establish a MALoS. Using a specified pipe network VI value should be more reliable than assessing pipe RSL based solely on the pipe Str.Fl, i.e., a certain breakage rate. Because VI includes the HCl, water AI, and SCI indices in addition to Str.Fl. In the present situation, the VI values were converted into linguistic terms expressing the LoS. When the VI is very low, i.e., VI ≤ 0.20, the LoS is considered as Excellent. LoS is Very good for 0.20 < VI ≤ 0.30, Good when 0.3 < VI≤ 0.6, Medium if 0.6 < VI ≤ 0.75, Fair for 0.75 < VI ≤ 0.85. Finally, LoS is considered Bad if 0.85 < VI ≤ 0.95 and Very Bad for VI values higher than 0.95.

Figures 3a and 3b show that the SLP graphs for the smallest (100 mm) and the largest (400 mm) CI pipes with a selected minimum LoS as ‘Fair’. The WARRM possesses an SLP library that contains 51 SLP graphs, one for each pipe group. These figure suggest that the minimum established LoS will be reached after 94 and 87 years for the smallest and the largest CI pipes, respectively. At this time, the asset managers should take rehabilitation actions in order to increase the LoS. Presently, the City of Kelowna performs lining, re-lining, and cathodic protection for the rehabilitation of water
mains, therefore, the same rehabilitation practices are applied to evaluate WARRM practicality here as well. By lining the pipe, its VI should decrease from the threshold value to a certain level and the LoS should increase. The tool allows the managers to select from a drop-down list button a certain percentage of the VI threshold value to express that. After a certain number of years, the pipes will start deteriorating again, and VI will increase and reach the VI threshold value corresponding to the minimum selected LoS, i.e., at the age of 101 years for the smallest pipes (100 mm) and 90 years for the largest. The process would be repeated for a certain number of rehabilitation actions as illustrated by Figures 3a and 3b.

### 3.2.3. Decision-making

This section explains how the improved decisions can be made using the LCC analysis for the two CI pipes under investigation, i.e., the smallest (100 mm) and the largest (400 mm). The smallest CI pipe, installed in the year 1972, with an ID number (from City of Kelowna database) of 125295 is 178.752 m long. The deterioration curve and (remaining) SLP graph developed for the CI pipes of 100 mm (Figures 2a and 3a) are used, the same minimum LoS (Fair) and the above-mentioned rehabilitation actions, i.e., (1) lining, (2) re-lining, and (3) cathodic protection, are considered. For instance, after these three actions, the pipe should be replaced according to the utility manager. The costs for the pipe rehabilitation actions and repairing the subsequent breaks over each extended service “life” due to these rehabilitation actions are computed with the new remaining (extended) service life of the pipe. The actual costs of these actions were

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**Table 1. Summary of the deterioration curve function coefficients for all the 51 pipe groups.**

| No. | Pipe group         | Coefficients | No. | Pipe group         | Coefficients |
|-----|--------------------|--------------|-----|--------------------|--------------|
| 1   | CI_Φ_100 mm        | α = 0.00090  | 27  | AC_Φ_450 mm        | α = 0.00132  |
| 2   | CI_Φ_150 mm        | β = 0.07197  | 28  | AC_Φ_500 mm        | β = 0.07026  |
| 3   | CI_Φ_200 mm        | α = 0.00090  | 29  | CONC_Φ_500 mm      | β = 0.07013  |
| 4   | CI_Φ_250 mm        | β = 0.07202  | 30  | CONC_Φ_600 mm      | β = 0.07023  |
| 5   | CI_Φ_300 mm        | β = 0.07214  | 31  | CONC_Φ_900 mm      | β = 0.07009  |
| 6   | CI_Φ_350 mm        | β = 0.07209  | 32  | PVC_D_50 mm        | β = 0.06858  |
| 7   | CI_Φ_400 mm        | β = 0.07218  | 33  | PVC_Φ_100 mm       | β = 0.06859  |
| 8   | DI_Φ_100 mm        | β = 0.07197  | 34  | PVC_Φ_150 mm       | β = 0.06868  |
| 9   | DI_Φ_150 mm        | β = 0.07204  | 35  | PVC_Φ_200 mm       | β = 0.06858  |
| 10  | DI_Φ_200 mm        | β = 0.07201  | 36  | PVC_Φ_250 mm       | β = 0.06859  |
| 11  | DI_Φ_250 mm        | β = 0.07199  | 37  | PVC_Φ_300 mm       | β = 0.06860  |
| 12  | DI_Φ_300 mm        | β = 0.07197  | 38  | PVC_Φ_350 mm       | β = 0.06858  |
| 13  | DI_Φ_350 mm        | β = 0.07196  | 39  | PVC_Φ_400 mm       | β = 0.06857  |
| 14  | DI_Φ_400 mm        | β = 0.07197  | 40  | PVC_Φ_450 mm       | β = 0.06857  |
| 15  | DI_Φ_450 mm        | β = 0.07196  | 41  | PVC_Φ_500 mm       | β = 0.06857  |
| 16  | DI_Φ_500 mm        | β = 0.07197  | 42  | PVC_Φ_600 mm       | β = 0.06859  |
| 17  | DI_Φ_600 mm        | β = 0.07196  | 43  | PVC_Φ_750 mm       | β = 0.06857  |
| 18  | DI_Φ_750 mm        | β = 0.07196  | 44  | HDPE_Φ_50 mm       | β = 0.06859  |
| 19  | DI_Φ_135 mm        | β = 0.07197  | 45  | HDPE_Φ_200 mm      | β = 0.06858  |
| 20  | AC_Φ_100 mm        | β = 0.07005  | 46  | HDPE_Φ_812 mm      | β = 0.06858  |
| 21  | AC_Φ_150 mm        | β = 0.07011  | 47  | COP_Φ_25 mm        | β = 0.07198  |
| 22  | AC_Φ_200 mm        | β = 0.07007  | 48  | COP_Φ_38 mm        | β = 0.07196  |
| 23  | AC_Φ_250 mm        | β = 0.06987  | 49  | COP_Φ_50 mm        | β = 0.07196  |
| 24  | AC_Φ_300 mm        | β = 0.07011  | 50  | STEEL_Φ_500 mm     | β = 0.07198  |
| 25  | AC_Φ_350 mm        | β = 0.07003  | 51  | GALV_Φ_50 mm       | β = 0.07196  |
| 26  | AC_Φ_400 mm        | β = 0.07049  |     |                    |              |

Notes: Φ = Pipe diameter, CI = Cast iron, DI = Ductile iron, AC = Asbestos cement, PVC = Polyvinyl chloride, HDPE = High-density poly ethylene, COP = Copper, & GalV = Galvanized (water mains)
The WARRM can consider different discount rates (i.e., 3%, 4%, 5%, and so on). The user has to select the desired discount rate. In this example, a discount rate of 3% is used. The total costs for each step (e.g., lining costs plus subsequent break repair costs until it is time for a new rehabilitation action) are compared with the costs for the pipe replacement scenario when the minimum LoS is reached. If the ratio between the pipe "rehabilitation action added up with the break repair costs until the next rehabilitation action should be expected" and the pipe "replacement costs added up with the costs for repairing the pipe breaks until the next rehabilitation action should be expected" is less than 1, it is better to rehabilitate the pipe instead of replacing it (the tool automatically returns the term 'Repair' in this case). Otherwise, the term 'Replace' will be returned by the tool. Table 2 shows the summary of comparison between the costs for the described rehabilitation scenario and the various costs for the pipe replacement i.e., at the time of Action 1, Action 2, Action 3, etc.

In Table 2, the first row (each principal row is constituted by at least three 'sub-rows') below the header is used to explain how to read this table to avoid confusion. For the first column, below the header "Rehabilitation Action", the type of action selected by the utility manager from a drop-down list button in the tool appears (for instance, lining). Besides the action, the year (in this case, 2066) for taking this action automatically appears once the pipe was selected (or written) by the utility manager from the corresponding drop-down list button in the tool. Below, the costs for this rehabilitation action added up to the costs for the pipe breaks repair (until the next rehabilitation action is expected) are displayed (i.e., $934,511). The next column, under the header "Pipe Replacement" shows the alternative scenario, here this is the (pipe) "replacement instead of (taking) Action 1" (i.e., lining). Besides, the year for this pipe replacement (i.e., 2066) is also displayed. Below, the costs for replacing the pipe added up with the costs of repairing the pipe breaks (until the next rehabilitation action) is displayed (i.e., $12,539).

Table 2. Example of LCC analysis for a rehabilitation scenario of various interventions compared to a replacement action taken at the time of each rehabilitation action for the 100 mm CI pipe (ID: 125295) installed in the year 1972. For cost ratios between each rehabilitation scenario and its replacement scenario counterpart equal or greater than 1, "replace the pipe" is the decision suggested.

| Rehabilitation Action | Versus | Date (year) | Pipe Replacement | Date (year) | Cost Ratio | Decision |
|-----------------------|-------|-------------|------------------|-------------|------------|----------|
| Action 1              | Lining| 2066        | Replacement instead of Action 1 | 2066 | 74.53 | Replace the pipe |
| Action 2              | Lining| 2073        | Replacement instead of Action 2 | 2073 | 74.35 | Replace the pipe |
| Action 1 and 2        | Lining| 2066        | Replacement at time of Action 1 | 2066 | 4.60  | Replace the pipe at time of Action 1 |
| Action 3              | Cathodic Protection | 2080 | Replacement instead Action 3 | 2080 | 32.42 | Replace the pipe |
| Action 1, 2 and 3     | Lining| 2066        | Replacement at time of Action 1 | 2066 | 4.79  | Replace the pipe at time of Action 1 |
| Action 1, 2 and 3     | Cathodic Protection | 2073 | Replacement at time of Action 2 | 2073 | 1.94  | Replace the pipe at time of Action 2 |

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| Action 1 and 2        | Lining| 2066        | Replacement at time of Action 1 | 2066 | 4.60  | Replace the pipe at time of Action 1 |
| Action 3              | Cathodic Protection | 2080 | Replacement instead Action 3 | 2080 | 32.42 | Replace the pipe |
| Action 1, 2 and 3     | Lining| 2066        | Replacement at time of Action 1 | 2066 | 4.79  | Replace the pipe at time of Action 1 |
| Action 1, 2 and 3     | Cathodic Protection | 2073 | Replacement at time of Action 2 | 2073 | 1.94  | Replace the pipe at time of Action 2 |

The WARRM can consider different discount rates (i.e., 3%, 4%, 5%, and so on). The user has to select the desired discount rate. In this example, a discount rate of 3% is used. The total costs for each step (e.g., lining costs plus subsequent break repair costs until it is time for a new rehabilitation action) are compared with the costs for the pipe replacement scenario when the minimum LoS is reached. If the ratio between the pipe "rehabilitation action added up with the break repair costs until the next rehabilitation action should be expected" and the pipe "replacement costs added up with the costs for repairing the pipe breaks until the next rehabilitation action should be expected" is less than 1, it is better to rehabilitate the pipe instead of replacing it (the tool automatically returns the term 'Repair' in this case). Otherwise, the term 'Replace' will be returned by the tool. Table 2 shows the summary of comparison between the costs for the described rehabilitation scenario and the various costs for the pipe replacement i.e., at the time of Action 1, Action 2, Action 3, etc.

In Table 2, the first row (each principal row is constituted by at least three 'sub-rows') below the header is used to explain how to read this table to avoid confusion. For the first column, below the header "Rehabilitation Action", the type of action selected by the utility manager from a drop-down list button in the tool appears (for instance, lining). Besides the action, the year (in this case, 2066) for taking this action automatically appears once the pipe was selected (or written) by the utility manager from the corresponding drop-down list button in the tool. Below, the costs for this rehabilitation action added up to the costs for the pipe breaks repair (until the next rehabilitation action is expected) are displayed (i.e., $934,511). The next column, under the header "Pipe Replacement" shows the alternative scenario, here this is the (pipe) "replacement instead of (taking) Action 1" (i.e., lining). Besides, the year for this pipe replacement (i.e., 2066) is also displayed. Below, the costs for replacing the pipe added up with the costs of repairing the pipe breaks (until the next rehabilitation action) is displayed (i.e., $12,539).
action should be expected) are displayed (i.e., $12,538). The third column (cost ratio) shows the ratio between the costs for Action 1 (first column) and the costs for the pipe replacement scenario (second column). For this specific pipe, this ratio is 74. Finally, the last column shows the decision suggested by the tool based on this ratio. In this example, the decision is “Replace the pipe” instead of rehabilitating it by lining because the ratio is higher than 1. Then, for the purpose of the tool illustration and/or verification, if the manager decides to rehabilitate the pipe, a similar analysis is shown in the second row (constituted by tree ‘sub-row’: i) Action 2, ii) Lining, and iii) Costs ($) and so on.

Table 2 suggests that in the first case, the minimum LoS will be reached in 2066. After this, Action 1 (lining) would be taken. The costs for this action and the repair costs of the subsequent pipe breaks (until reaching the new minimum LoS in the year 2073) would be much higher than those for replacing the pipe in the same year of Action 1 (i.e., 2066). The pipe replacement scenario includes the cost of repairs until 2073, this would be the year for taking Action 2, as the new minimum LoS will be reached according to the pipe rehabilitation scenario. Similarly the comparison between the costs of Action 2 (re-lining), expected for the year 2073 (if the pipe is rehabilitated by lining instead of replaced), including the subsequent (until the year 2080) pipe break repairs’ costs, on one hand, and, in another hand, the costs of alternative “pipe replacement at the time of Action 2” (i.e., in the year 2073) can also be seen in Table 2. The situation is not different for Action 3 (cathodic protection), except that the cost ratio (32.35) is lower than the ratios obtained from previous two actions (Table 2).

Table 2 also suggests that it is more cost effective to replace the pipe at the time estimated for Action 1, instead of taking Action 1 and Action 2 in the years 2066 and 2073 respectively. The ratio between the “costs for Action 1 and the break repairs plus the costs for Action 2 and the break repairs until the time to take Action 3”, on one hand, and, in another hand, the “costs for the pipe replacement at the time of Action 1 plus the costs for repairing the breaks of the new pipe until the time to take Action 3” decreases but remains higher than 1 (i.e., 4.6). The situation is similar if the combined costs for Actions 1, 2, and 3 (including cost of repairs for breaks until Action 4 is required) are compared to those for the pipe replacement (at the time of Action 1) and for repairing the breaks of the new pipe until Action 4 is needed, the cost ratio, in this case, is 4.8. The ratio decreases (from 4.8 to 1.94) but, remains higher than 1, if the same pipe rehabilitation scenario (Actions 1, 2, and 3) is compared to the action “replacing the pipe at the time of Action 2.

The largest CI main (ID 125298), which has a diameter of 400 mm, a length of 104.41 m, and was installed in 1957, has been investigated. Table 3 presents the summary of the costs for the various rehabilitation and replacement scenarios discussed previously for the smallest CI water main. This table shows that the decisions suggested for the largest CI water main (i.e., ID 125298) about R/R are identical with those suggested for the pipe ID 125295. The cost ratios between each rehabilitation scenario and its replacement scenario counterpart are all greater than 1. The ratios came out to be 5.73, 5.70, 2.03, 2.63, 2.24, and 1.46, respectively (refer to Table 2 for comparison with pipe ID 125295).

It is important to note that these results are specific to the pipes investigated (ID 125295 and ID 125298) above. The results could be different for two different cast iron (or ductile iron) pipes of the same sizes, primarily due to different hydraulic and environmental (site specific) conditions. While for each group of pipes only one deterioration curve is used, each pipe has its specific breakage rate (number of breaks/year/kilometer). This might, in turn, have an impact on the repair costs and ultimately on the cost ratios. For water mains exhibiting identical costs over their life cycle, the failure risk index developed by Francisque et al. (2014) can be used for their final prioritization. In this case, priority for

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**Table 3.** Example of LCC analysis for a rehabilitation scenario of various interventions compared to a replacement action taken at the time of each rehabilitation action for the 400 mm CI pipe (ID: 125298) installed in the year 1957. For cost ratios between each rehabilitation scenario and its replacement scenario counterpart equal or greater than 1, “replace the pipe” is the decision suggested.

| Rehabilitation Action | Versus | Pipe Replacement | Decision |
|-----------------------|--------|------------------|----------|
| Action 1              | Date (year) | Replacement instead of Action 1 | Cost Ratio | Replace the pipe |
| Lining                | 2044   | 11,200           | 5.73     |
| Costs ($)             | 64,203 |                  |          |
| Action 2              | Date (year) | Replacement instead of Action 2 | Cost Ratio | Replace the pipe |
| Lining                | 2051   | 11,723           | 5.70     |
| Costs ($)             | 66,849 |                  |          |
| Actions 1 and 2       | Date (year) | Replacement at time of Action 1 | Cost Ratio | Replace the pipe at time of Action 1 |
| Lining                | 2044   |                  |          |
| Costs ($)             | 2073   | 64,677           | 2.03     |
| Action 3              | Date (year) | Replacement instead Action 3 | Cost Ratio | Replace the pipe |
| Cathodic Protection   | 2058   | 12,148           | 2.63     |
| Costs ($)             | 31,976 |                  |          |
| Actions 1, 2 and 3    | Date (year) | Replacement at time of Action 1 | Cost Ratio | Replace the pipe at time of Action 1 |
| Lining                | 2044   |                  |          |
| Costs ($)             | 2051   | 72,869           | 2.2479   |
| Cathodic Protection   | 2058   |                  |          |
| Costs ($)             | 163,028| 111,969          | 1.46     |
appropriate R/R actions should be given to the pipe with more severe consequences in case of failure, given that the same level of likelihood of failure or vulnerability (MALoS) is set by the utility manager for all the pipes to estimate the time to take R/R actions. Details can be found in Francisque et al. (2014).

The results revealed that the WARRM can be efficiently used for R/R planning of water mains with available technical and financial resources in small to medium sized utilities. The WARRM is implemented into Microsoft Excel which is, even in the small utilities, a well-known, readily available, and easy to use software. Therefore, it does not require highly qualified personnel, for which there is a lack in the small to medium utilities. Moreover, most of the time the tool allows the user to define the desired values using some drop-down list buttons. Globally, its graphic user interface is friendly and familiar. The tool is also linked to a GIS which allows the user to visualize the network (mapping of various indices like soil corrosiveness, pipe hydraulic capacity, vulnerability, consequences of failure as well as the risk of failure) and make spatial analysis for more informed decision-making.

Nevertheless, the model for predicting the future pipe breaks for a given WSN must be derived specifically from its historical patterns related to the pipes’ breakage rates. However, usually, the data for identifying these patterns are missing or incomplete and contain many uncertainties. This particular situation can be a major obstacle in the process of creating the tool for smaller utilities.

4. Conclusions

A LCC based framework for WAter main Replacement Risk-based Model (WARRM) has been developed in this study to manage water mains for small to medium sized utilities. The model used likelihood of failure (or vulnerability) of the water mains to estimate their deterioration over time and remaining service life (RSL). The utility managers can estimate the most likely time to rehabilitate the pipes, they can also compare the impacts of different possible rehabilitation actions on the pipes’ RSL and their costs over the RSL. The model compares the costs of various R/R scenarios for each water main to suggest the most cost effective decision. Based on this comparison a recommendation is displayed about the pipe’s R/R at a given year. Overall, WARRM proved that it can be efficiently utilized by the utility managers of small to medium sized utilities to assess the risk of failure of their water infrastructure, strategically manage the risk, and optimally plan and allocate their limited human and financial resources over the pipe’s life cycle.

The modeling framework has been implemented on the WSN of the City of Kelowna to evaluate its practicality. The pipe deterioration curves have been developed using the City record of water main breaks. Therefore, these curves are specific to this case study. However, the approach and the frameworks developed can be used for any similar WSN and even for larger water utilities as far as the necessary adjustments according to the utility characteristics and available data can be made. The model can be further greatly refined by improving the input data, by gathering and considering new data. As a future research, different weights can be considered for different years during the analysis to develop more accurate pipe breakage rate models and deterioration curves.

Note

1. It is important to highlight that this satisfaction of the consumer based on the water main VI does not obviously exclude his satisfaction related to compliance with regulations and guidelines about the water microbial quality and its aesthetic properties (e.g., colour, taste, and odour).

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