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PERFORMANCE ASSESSMENT FOR WATER NETWORKS

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Abstract: Water networks (WNs) are responsible of providing adequate amounts of safe water to the public. As other critical infrastructure systems, water networks are subjected to deterioration which increases the number of breaks and leaks and lower water quality. Given, aging infrastructure and tight budgets, there is a rapidly increasing need for efficient rehabilitation programs to maintain the sustainable and cost-effective functionality of WNs. The first step towards developing such planning programs is to assess the performance of water assets. This paper introduces a novel model for assessing the performance of water networks. Water network consists of several pipeline segments. Water pipelines are clustered into homogenous groups based on their characteristics. Weibull Probability Distributions are then utilized to model the time between failures, censored data, and thus estimate the reliability as well as the deterioration of these pipes. Subsequently, the criticality of water pipelines is elicited to serve as a prioritizing tool that asserts more weight of importance on the pipes of significant social, environmental and economic consequence of failure. Multi Attribute Utility Theory (MAUT) is adopted to calculate the performance of each segment. The evaluating of WN performance that can be derived using this approach will assist utility managers to accurately construct comprehensive maintenance and rehabilitation programs for the components, segments and entire.

1 Introduction

The US Department of Homeland Security defined 18 critical infrastructure systems whose continuous function must be secured and quickly restored following to any disruption (Gay and Sinha 2013). Critical infrastructure systems include systems that transport people and goods, deliver drinking water, handle waste, and protect city against natural hazards. Water supply networks are those responsible of providing adequate amounts of safe, high quality, water to the public. Ensuring the proper function of this system has always been a major concern for utilities managers due to its direct impact on the health and safety of people. CIRC (2016) indicates that 35% of water assets in Canada require a critical attention and there is a significant gap between the needed and the implemented investments. Moreover, according to the CIRC (2016), the estimated replacement cost is almost CAD 60 billion. Such facts raise an alarming call for some immediate and long-term plans to address the situation. Therefore, the main aim is to develop a model to assess the performance of water distribution networks which can be used later for budget allocation and maintenance scheduling purposes. To achieve that purpose, the following objectives need to be satisfied:

1. To develop a model that assess the reliability of water mains.
2. To develop a model that assess the criticality of water mains.
3. To aggregates the afore-mentioned models into a single performance assessment tool.

This paper provides a detailed illustration of the first model as a part of a more comprehensive performance assessment tool.

2 Background

Several techniques have been developed to assess the condition and the performance of water networks. El-Abbasy et al. (2016) introduced an integrated performance assessment model for water network based on the performance of the pipelines and accessorises. In their study, they employed the reliability theory and multiattribute utility theory to assess the performance of each segment, sub-network and networks (El-Abbasy et al. 2016). Earlier, Clair and Sinha (2011) developed a weighted factor and fuzzy-based approach to forecast the performance of metallic water pipelines. Fares and Zayed (2010) introduced a methodology to assess the risk associated with the failure of water mains using a hierarchical fuzzy expert system. Salman et al. (2009) implemented analytical hierarchy process (AHP) and simple multi attribute rating technique (SMART) to assess the reliability of water segments and its components. In 2009, Zhou et al. established a condition assessment tools for water mains by employing analytic hierarchy process (AHP) and fuzzy PROMETHEE II method to calculate pipe breakage risk as a proxy of the pipe condition. Azhar Uddin (2016) employed minimum cut analysis technique to suggest an integrated reliability assessment of water networks. In his work, he developed two models to assess the mechanical and hydraulic reliability of water networks.

Despite the previous efforts in trying to address the performance assessment of water networks, several draw backs can be realized. Condition assessment models attempt to evaluate te performance of water networks based on several quantitative and qualitative factors. Such approach requires extensive data collection with significant part being subjected to biased judgments and uncertainty. On the other hand, most of the previously developed models to asses the performance of water networks assumed a constant failure rate in forecasting the reliability of the pipelines. While this assumption is made to simplify the computations, it’s not accurately capturing the exact behavior of these assets. In this study the time between failures are fitted to present the best distribution that describes the failure history profile of each pipeline segment. Next, the parameters of theses distributions are used in the survivability equation to calculate the reliability of each water main.

3 Data Collection

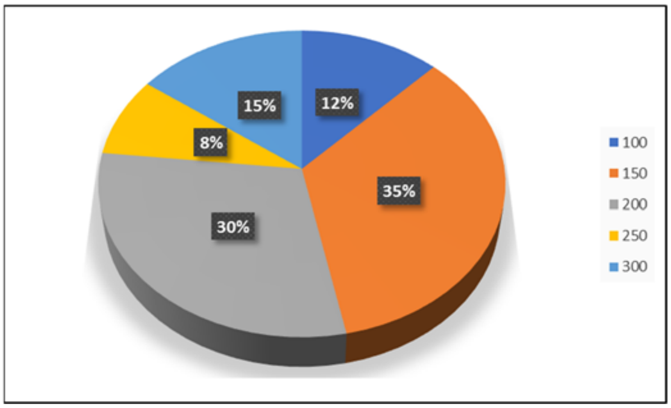
The City of London was incorporated in 1855 and rapidly established itself as a business hub in southern Ontario. The City owns a water network of more than 24,000 mains some of them were installed back in 1900 and still active till today. Figure 1 shows that over 97% of the City’s network is either cast iron, ductile iron, or PVC with diameter size <300mm. The City of London shared their data base inventory with the authors for the purpose of this research. The extracted data include data related to the characteristics of the pipeline, installation data, surrounding environmental condition, and breakage data. The breakage data include the order, time, and type of each observed break in the network. All the data were provided as GIS layers. The below steps were followed to prepare the data for modelling:

1. Pipe beaks dates that were missing or precede the installation dates were omitted.
2. Pipes that have significant time to first failure were excluded from modeling. This step is essential to avoid the bias resulting from intervention and major rehabilitation works that were implemented on those pipes.
3. Data cleaning was done to eliminate miscoded data like those whose installation date, or failure date, is sometime in the future.

4 Reliability Model

As mentioned earlier, breakage data of a huge water distribution network were provided by the City of London, Ontario. These data were used to build the reliability assessment model in this study. Nevertheless, the following data preprocessing steps were conducted first:

1. The number of breaks in each pipe was counted and linked to that specific pipe. The provided data include several GIS layers that were not linked to each other. For example, the mains layer was not linked to the breaks data. Hence, a joining approach was needed to link the breaks to each pipe. This linking and counting was done using GIS and Matlab.



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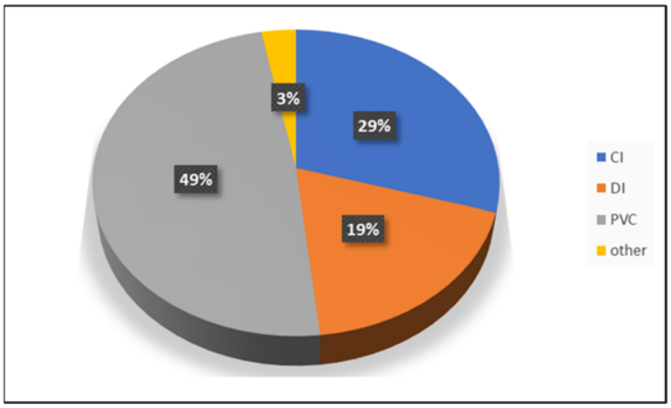

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Figure 1 : Distribution of Pipe a) size b) material

2. The inter-failure time was calculated to get the time to the n^{th} failure. The observed data is right censored data in which failure starting the inter-failure time series has occurred unlike the failure event ending it. This is to say that the ending failure is yet to occur sometime in the future.

After the inter-time failure was calculated for all the mains, they were clustered into homogeneous groups baes on their material type and size. Five main groups resulted form this clustering namely: mains that are made of CI and of size <150mm, mains that are made of CI and of size >150mm, mains that are made of DI and of size <150mm, mains that are made of DI and of size >150mm, and others. Weibull distribution parameters were then obtained by fitting the time between each successive failure, breaks. These fittings along with the needed checks were performed using Minitab software and Matlab. The time to next failure was modeled as either a 2-parameter or a 3-parameter Weibull distribution. The probability function for the 3-parameter Weibull distribution can be given by Equation 1:

$$[1]\ f(T,\beta,\eta,\gamma) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$

Where: $T \geq 0$, $\beta > 0$, $\eta > 0$, $-\infty \leq \gamma \leq \infty$

And: β is the shape parameter,

η is the scale parameter,

γ is the location parameter.

According to the value of the shape parameter β, the Weibull distribution cab be related to several other probability distributions such as normal, exponential, Rayleigh and other distributions. A Weibull distribution with β less than one corresponds to a decreasing failure rate over time, improving reliability. This phase is known as infant mortality phase or early-life failures. On the other hand, the Weibull distribution with β more than one corresponds to an increasing failure rate over time, deteriorating reliability. This phase is known as wear out phase or end-life failures. In special cases when the Weibull distribution has a shape parameter β that is exactly one, this corresponds to a constant failure rate. In this case, the Weibull distribution is reduced into an exponential one indicating a Poisson process. The scale parameter η determined the scale of the Weibull distribution. A higher value of η corresponds to a lower failure rate higher reliability. The location parameter γ describes the shift, time offset, of the distribution. When the value of the location parameter is set to zero, the distribution is reduced a 2-parameter Weibull distribution. The reliability, survivability, for the 3-parameter Weibull distribution can be given by Equation 2:

[2] $R(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$

And the failure rate is calculated as shown in Equation 3:

[3] $\lambda(T) = \left(\frac{\beta}{\eta}\right)\left(\frac{T-\gamma}{\eta}\right)^{\beta-1}$

Where $T \geq 0$ is the duration, $\beta > 0$ is the shape parameter, $\eta > 0$ is the scale parameter, and $-\infty \leq \gamma \leq \infty$ is the location parameter. Table 1 summarizes a sample of the results for the cohort of pipelines that are made of ductile iron and of a nominal size that is less than 150mm. In general, 3-parameter Weibull distribution produces a finer fitting for data related to the time to first failure while 2-parameter Weibull distribution generated better fittings for subsequent failures. This can be clearly observed in figure 2 which illustrates the results of Anderson-Darling (AD) test. The Anderson-Darling statistic measures how well the data follow a certain distribution and is used to compare the fit of several distributions to determine which one is the best. A higher p-value and lower AD indicate a better fit. Figure 2 shows that the p-value of the 3-paramert Weibull distribution is the highest (0.466) and the AD value is the lowest (0.366). Hence, this distribution is the best to describe the data related to the time to the first failure of pipelines that are made of ductile iron and of diameter that is less than 150mm.

Table 1: Parameters of the Weibull fitting for each data set.

State	Scale Parameter η	Shape Parameter β	Location Parameter γ
Time to 1st failure	15.9589	1.6303	-2.2302
Time to 2nd failure	8.8346	0.9209	None
Time to 3rd failure	9.8017	1.4361	None
Time to 4th failure	4.8996	1.1154	None

Figure 3 displays the probability density function obtained by fitting the duration data to the first failure of pipelines that are made of ductile iron and of diameter that is less than 150mm. It can be observed that the distribution starts at location to the left of the origin, before zero, because of the location parameter effect $\gamma = -2.2302$. Reliability curve for this cohort (DI <150mmm) is shown is Figure 4. The graph indicates that there is a probability of 52% for a water main from this cohort (DI <150mm) to survive ten years without experiencing the first failure. It should be noted that once the distribution parameters are determined, other distributional characteristics cab be readily obtained. Mean time to failure, duration in a certain break order and quantile statistics are examples of these characteristics.

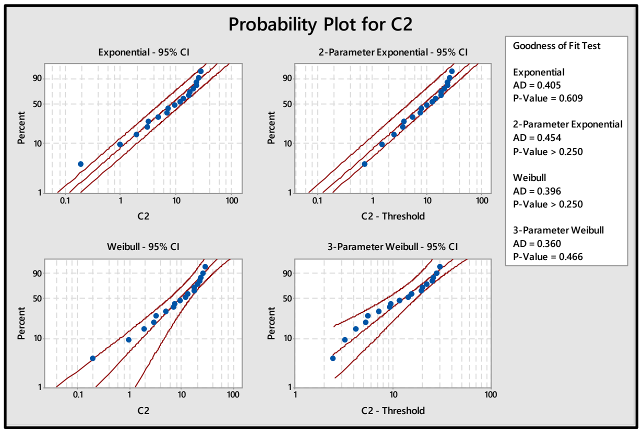

Figure 2 Different probability distribution fitting for time to 1st failure (DI<150mm)

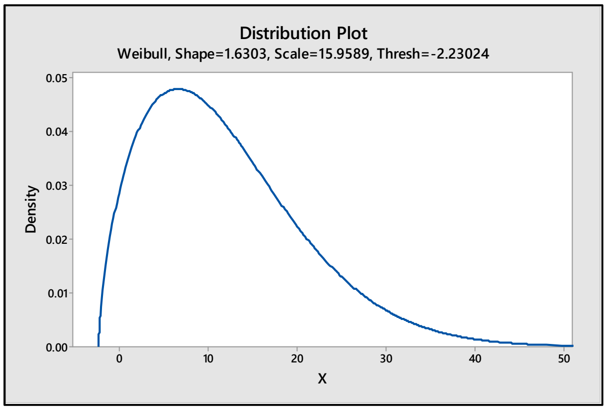

Figure 3 Probability density function of time to 1st failure (DI<150mm)

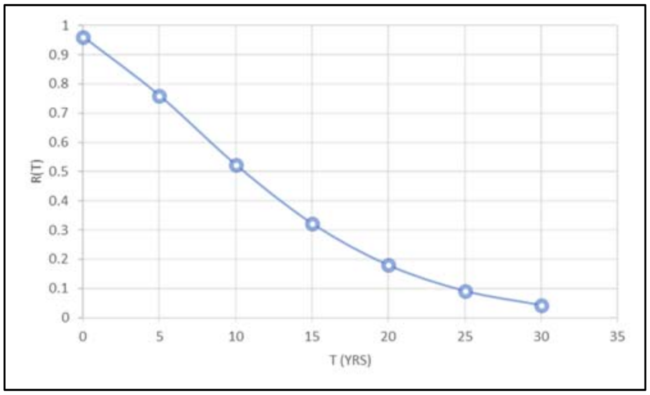

Figure 4 Reliability, survival, function durations for cohort (DI <150mmm)

5 Performance Model

The proposed performance model is determined based on the aggregation between the reliability and criticality assessment of water pipelines. This can then be extended to include other components of water distribution network and thus develop a performance assessment model of the segments, sub-networks, and networks. Multi-attribute utility theory (MAUT) is employed to aggregate the reliability with the criticality of each pipeline as shown in equation 4:

[4] $PI = \sum_{i=1}^{n} R_i \times C_i$

Where PI is the performance index, R_i is the reliability of water pipeline i , C_i is the criticality of pipeline i, and n = number of water pipelines. The Decision through MAUT is based on a utility function. This function is defined according to the desired preferences and the used parameters that the decision maker aims to maximize The application consists of the following actions 1) identify the several alternatives that should be assessed; (2) establish the list of criteria that will be considered in the evaluation process; (3) assign a value to each criterion on a unified scale; (4) compute the overall 'score' of an alternative using the weighted sum of its rating against each criteria as shown in Equation 2.18; and (5) rank the alternatives bytheir relative scores . Finally, several techniques can be utilized to estimate the performance of water sub-networks and networks by aggregating the performance indices of water segments such as cut set, path set, connectivity ranked matrix and others.

6 Conclusion

This study introduced a performance assessment model for water mains based on the reliability and criticality assessments. The reliability model utilizes Weibull distribution curves to fit the inter-failure time and estimate the distribution parameters. These parameters can then be used to calculate the survivability, reliability, of the pipelines at any time. Attention should be paid to assure that the data used in this process is right-censored data. subsequently, a criticality assessment model is to be developed and coupled with the above developed reliability model. Multi-attribute utility theory is then used to aggregate the reliability of the water pipelines where the criticality of each pipeline is used as weighting factor in the equation. The authors are considering extending the developed model to other water network assets like valves, hydrants, and other accessories. The global performance index can be used as a basis for optimizing the scheduling of rehabilitation actions for water networks as well as budget allocation strategies.

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