RELIABILITY ANALYSIS OF WATER DISTRIBUTION NETWORKS USING MINIMUM CUT SET APPROACH

Azhar Uddin Mohammed\textsuperscript{1,3}, Tarek Zayed\textsuperscript{1}, Osama Moselhi\textsuperscript{1} and Alaa Alhawari\textsuperscript{2}

\textsuperscript{1} Building, Civil and Environmental Engineering, Concordia University, Canada
\textsuperscript{2} Department of Civil Engineering, Qatar University, Qatar
\textsuperscript{3} m_fnu@live.concordia.ca

Abstract: Canadian Water and Wastewater Association (CWWA) estimated the cost to replace 112,000 km of water mains in Canada to be 34 billion Canadian Dollars. Reliability analysis of water distribution networks (WDNs) is an important aspect in planning and operation of a WDN and hence plays an important role in the efficient use of allocated budget. In general, reliability analysis is classified into mechanical reliability and hydraulic reliability. Mechanical reliability is defined as the ability to function even when some components are out of service or there is any mechanical break. Hydraulic reliability is concerned with delivery of the specified quantity of water to a specific location at the required time under the desired pressure. This paper introduces a methodology for evaluating mechanical reliability of WDNs using the minimum cut set approach. The methodology involves the computation of mechanical reliability at the component (pipe, hydrant etc.), segment (collection of pipes and components) and network levels. An illustrative example is worked out to demonstrate the use of the developed methodology.

1 INTRODUCTION

Water distribution networks (WDN) are complex interconnected networks consisting of sources, pipes, and other hydraulic control elements such as pumps, valves, regulators, tanks etc., that require extensive planning and maintenance to ensure good quality water is delivered to all customers (Shinstine et al., 2002). These networks are often described in terms of a graph, with links representing the pipes, and nodes representing connections between pipes, hydraulic control elements, consumers, and sources (Ostfeld et al., 2002). They are vital part of urban infrastructure and require high investment, operation and maintenance costs. The main task of WDN is to provide consumers with a minimum acceptable level of supply (in terms of pressure, availability, and water quality) at all times under a range of operating conditions. The degree to which the network is able to achieve this, under both normal and abnormal conditions, is termed its reliability. (Atkinson et al., 2014). Hence, reliability is considered as an integral part in making decisions regarding the planning, design, and operation phases of WDNs.

Many researchers defined reliability based on different conditions. Al-Zahrani and Syed (2005) defined reliability of WDN as its ability to deliver water to individual consumers in the required quantity and quality and under a satisfactory pressure head. Kalungi and Tanyimboh (2003) defined reliability as the extent to which the network can meet customer demands at adequate pressure under normal and abnormal operating conditions. In general reliability of any network refers to its ability of performing a mission placed on it, adequately under stated environmental conditions and for a prescribed time interval.

No network is entirely reliable. In every network, undesirable events, i.e. failures, can cause decline or interruptions in the network performance (Ostfeld 2004). Reliability of WDNs relates to two types of failure, (1) mechanical failure of network components and (2) hydraulic failure caused by changes in
demand and pressure head. Mechanical reliability reflects the degree to which the network can continue to provide adequate levels of service during unplanned events such as mechanical failure (e.g., pipe bursts, pump malfunction). Hydraulic reliability reflects how well the network can cope with changes over time, such as deterioration of components or demand variations (Atkinson et al., 2014). Some authors (Islam et al., 2014; Gupta et al., 2012) have also argued about water quality reliability which is assessed with respect to a predefined level or range of selected water quality parameters (e.g., residual chlorine concentration). If the water quality parameter is within the prescribed range, the WDN is considered reliable, otherwise it is considered unreliable for water quality. However, the scope of this paper is limited to the evaluation of mechanical reliability of WDN and its components.

According to Su et al. (1987), reliability of components in a WDN such as valves, hydrants, controls etc. has an effect upon, and must be used to determine, the overall network reliability. However, no model has been found in the literature evaluating reliability of components. In this paper, a methodology is developed to assess the reliability of components in a WDN, and using reliabilities of these components, segment reliability is evaluated. Then the overall network reliability is assessed using minimum cut set method.

2 BACKGROUND

A review of the literature reveals that there is no universally acceptable measure for the reliability of water distribution networks. It gained considerable research attention over the last few decades. This research has concentrated on methodologies for reliability assessment and for reliability inclusion in optimal design and operation of WDNs. This section provides a summary of these efforts.

As reliability is not a network property that can be measured directly, it should be assessed based on other characteristics of the network that can be directly measured or calculated. Ostfeld (2004) categorized reliability assessment methods into (1) connectivity/topological, (2) hydraulic and (3) entropy as a reliability surrogate. The reliability which is based on the concept of connectivity refers to measures associated with the probability that a given network remains physically connected by taking into account the topology of the network. This type of measure mainly serves the purpose of evaluating mechanical reliability. Shamsi (1990) and Quimpo & Shamsi (1991) incorporated the use of node pair reliability (NPR) as the network reliability measure. The NPR is defined as the probability that a specific source and demand nodes are connected. This definition corresponds to the probability that at least one path is functional between the source node and the demand node considered. Yannopoulos and Spiliotis (2013) focused on topology of network as a measure for analyzing mechanical reliability. They developed a methodology based on adjacent matrix of graph theory in order to determine connectivity among different nodes. Measures used within this category do not consider the level of service provided to the consumers during a failure. The existence of a path between a consumer and a node is only a necessary condition for supplying its required demands (Ostfeld, 2004).

The second category of reliability assessment i.e., hydraulic measure is concerned with the conveyance of desired quantities and qualities of water at required pressures to the appropriate locations at the appropriate times. Xu and Goulter (1999) used a probabilistic hydraulic approach, based on the concept of the first-order reliability method (FORM), to determine the capacity reliability of the water distribution network, which is related to the hydraulic and demand variation failures, and is defined as the probability that the nodal demand is met at or over the prescribed minimum pressure for a fixed network configuration under random nodal demands and random pipe roughnesses. Shinistine et al. (2002), coupled a cut-set method with a hydraulic steady state simulation model that implicitly solves the continuity and energy equations for two large scale municipal water distribution networks in the Tucson Metropolitan Area. The measure of reliability was defined as the probability of satisfying nodal demands and pressure heads for various possible pipe breaks in the water distribution network at any given time. Zhuang et al. (2011) presented a methodology for reliability and availability assessment of a WDN based on an adaptive pump operation. In response to a pipe break, pump operations were adapted using various sizes of pump combinations. In their method, they evaluate hydraulic reliability in terms of available water to fulfill desired demand.
Entropy, as a surrogate measure for reliability is the third category which has been used by several researchers for reliability assessment during recent years. The fundamental idea is to use Shannon’s (1948) entropy measure of uncertainty that quantifies the amount of information contained in a finite probability distribution, to measure the inherent redundancy of a network. In this regard, entropy is more related to the category of connectivity/topological analysis than to that of hydraulic reliability. It is assumed that distribution networks, which are designed to carry maximum entropy flows, are generally reliable (Ostfeld, 2004). A WDN with higher entropy is expected to cope better with simultaneous multi-pipe failure (Gheisi and Naser, 2014). Prasad and Tanyimboh (2008) used Flow Entropy, a statistical entropy measure for WDNs to show that surrogate reliability measure can be used effectively to improve reliability of multi-source networks. Tanyimboh et al. (2011) used statistical entropy and other surrogate measures such as network resilience, resilience index and modified resilience index, for the reliability assessment of WDN to assess the effectiveness of surrogate reliability measures in relation to more rigorous and accurate hydraulic reliability measures.

Among the most well-defined processes to determine the topological/mechanical reliability of a network is the process of minimum cut-set (Yannopoulos and Spiliotis, 2013). Tung (1985) discussed six techniques for WDN reliability evaluation and concluded that the cut-set method is the most efficient technique in evaluating the network reliability. The minimum cut-set approach is usually applied in order to investigate the topology of a WDN and the detection of its critical elements the failure of which will affect the network operation. The minimum cut-set is a set of network components which, when failed, causes failure of the network; but if just one component of the set has not failed, no failure of network occurs. Following the cut-set method, an estimation of mechanical reliability of the WDN can be achieved.

2.1 Identification of minimum cut sets

To identify the minimum cut sets of a network in a reduced computational time, a method generally used in power transmission networks for the same purpose has been adopted (Zhou et al., 2012). It involves 1) finding all possible paths from the source node to the demand node, 2) Constructing a path matrix and 3) getting minimum cut sets from the path matrix.

A path is a connection between a source node and a demand node. This model considers a node to be adequately supplied as long as there is at least one link connecting it to the rest of the network which means that the network is not considered as failed even if there is a single path from the source node to the demand node. After finding all possible paths, a path matrix is constructed in which, number of rows is equivalent to the number of paths from source node to demand node under consideration, and number of columns is equivalent to the number of segments (or combinations of segments) in a network. This matrix is a zero-one matrix with 1 as its entry if the segment is present in the path to the demand node, and 0 as its entry if it is not. For example, there are 3 segments A, B and C in a network and the possible paths from the source node to the demand node are AB and AC. Then the path matrix is expressed as

\[
P = \begin{bmatrix}
1 & 1 & 0 \\
1 & 0 & 1
\end{bmatrix}
\]

Once the path matrix is constructed for the demand node under consideration, the network is analyzed for minimum cut sets. First order cut set is a single segment which when fails, causes the failure of entire network. Similarly, second order cut set is the combination of two segments, the combined failure of which causes the failure of entire network. If any column in a path matrix contains all elements as 1, then the segment corresponding to that column is recorded as a first order cut set. For example, all the elements of the first column are 1 in the matrix 1. Hence segment \{A\} is recorded as a first order cut set. To find the second order cut sets, create all combinations of 2 segments and construct a new path matrix by merging the elements as per the combinations. For example, combination of 2 segments for the above example network are \{A, B\}, \{B, C\} and \{C, A\}. New path matrix would be
From the matrix 2, combination of B and C results in a column with all elements as 1. Hence \{B, C\} is recorded as second order cut set. Note that, any combination with A is neglected because A is already a minimum cut set. The same procedure is followed for finding third and higher order cut sets with combinations of corresponding segments.

3 METHODOLOGY

This section discusses the various computing measures adopted to develop the methodology.

![Network Reliability Flowchart](image)

3.1 Failure rate

Most researchers have chosen failure rate as the primary indicator of reliability. Quantitatively, it is defined as the number of breaks per year per unit length. Breaks are considered one of the significant factors contributing to water losses and require substantial human effort and cost to repair such failures. As the number of breaks increases, the reliability of a WDN decreases. The most often applied formulae for estimating the pipe failure rate have been obtained using simple regression models on the available
Pipe failure data from a limited time period. In this paper, the pipe failure rate or breakage rate is computed using a regression model based on age of pipe, being developed in an ongoing research work at Concordia University. According to this model, the failure rate can be expressed as

\[ \lambda_{\text{pipe}} = 6 \times 10^{-5}X^2 + 0.0004X + 0.0026 \]

Where \( X \) is the age of pipe in years and \( \lambda_{\text{pipe}} \) is the failure rate of pipe expressed in number of breaks per year per unit length of pipe.

The failure rate of other components (hydrants, valves, controls) can be expressed as

\[ \lambda_{\text{component}} = \frac{N_f}{\text{length of segment}} \]

Where \( N_f \) is the number of failures per year and \( \lambda_{\text{component}} \) is the failure rate of component expressed in number of failures per year per unit length of segment.

### 3.2 Component reliability

After determining the failure rates of pipes and other components, the reliability is assumed to follow negative exponential distribution which would mean that reliability decreases exponentially as the failure rate increases with time, and can be computed as

\[ R_c = e^{-\lambda t} \]

Where \( R_c \) is the reliability of a component or pipe and \( \lambda t \) is the failure rate of a component or pipe.

### 3.3 Segment reliability

A segment is a single water main pipe or a group of connected pipes (along with all the associated components) which are usually located between two nearest intersections at which isolation valves may exist (Salman A., 2011). According to the definition, the segment reliability can be expressed as

\[ R_{\text{seg}} = \sum R_c \]

The above equation represents segment reliability where components have the same weight which is not true. Each component has its relative importance in a segment. To be more specific in determining segment reliability, a relative weight component \( (w_i) \) is included in equation 4 to adjust it.

\[ R_{\text{seg}} = \sum_{i=1}^{n} R_c w_i \]

Where \( i \) is the water main component, \( n \) is total number of water main components and \( w_i \) is the relative weight of component.

The relative weight of component \( (w_i) \) is the ratio of weight of component under consideration to the total weight of components in that particular segment. The weights of components are obtained from Salman A. (2011).

\[ \text{Relative Weight} \ (w_i) = \frac{\text{Weight of component}}{\text{Sum of weights of all components}} \]
3.4 Network reliability

The procedure for determining the network reliability of a WDN based on the minimum cut-set method is as follows.

3.4.1 Probability of failure of segments

Quantitatively, the probability of failure of a segment is the complement of the reliability of a segment. It can be expressed as

\[ Q = 1 - e^{-kt} \]

These segment failure probabilities are computed so that they can be used later for determining network reliability using minimum cut set method.

3.4.2 Identification of minimum cut sets

As described earlier in the literature review, all the minimum cut sets have to be identified to serve the purpose of evaluating network reliability.

![Figure 2: Identification of minimum cut sets](image)

3.4.3 Mechanical reliability of WDN based on Minimum Cut Set

According to Shinstine et al. (2002), for n components (segments) in the \( i \)th minimum cut set of a WDN, the failure probability of the \( j \)th component (segment) is \( Q_j \), which can be obtained by Eq. 7. The failure probability of the \( i \)th minimum cut set is

\[ Q(MC_i) = \prod_{j=1}^{n} Q_j \]

Where \( n \) is the number of segments in corresponding minimum cut set.

Assuming that the occurrence of the failure of the components within a minimum cut set are statistically independent. For example, if a water distribution network has four minimum cut sets, MC1, MC2, MC3, and MC4, for the network reliability, the failure probability of the network \( Q_N \), is then defined as follows (Billinton and Allan 1983):
[9] \( Q_N = Q(MC_1 \cap MC_2 \cap MC_3 \cap MC_4) \)

By applying the principle of inclusion and exclusion, equation 9 can be reduced to:

[10] \( Q_N = Q(MC_1) + Q(MC_2) + Q(MC_3) + Q(MC_4) = \sum_{i=1}^{4} Q(MC_i) \)

Where \( M \) is the number of minimum cut-sets in the network.

Finally, the mechanical reliability of the network can be expressed as:

[11] \( R_N = 1 - Q_N = 1 - \sum_{i=1}^{M} Q(MC_i) \)

4 CASE EXAMPLE

The hypothetical network shown in figure 3 is utilized for the demonstration of the developed methodology. The network consists of 8 segments named alphabetically and 7 nodes named numerically. Node 7 is a source node while the other nodes are demand nodes. Assuming the repair data for the network as shown in table 2, reliability of each component, each segment and whole network can be calculated. To calculate the reliability of presented hypothetical network using minimum cut sets method, network should be analyzed for the identification of minimum cut sets.

![Network Model](image)

Figure 3: Network model of case study

Let us consider node 3 as the demand node. The possible paths for the water to reach demand node 3 from source node 7 are found to be ABD, ACFED, ACFGH, and ABEGH and there are 8 segments. Therefore the path matrix can be constructed as

\[
\begin{bmatrix}
A & B & C & D & E & F & G & H \\
1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 0 & 1 & 1
\end{bmatrix}
\]

The elements in column A of matrix 3 are all 1. Hence \( \{A\} \) is recorded as a first order cut set. Note that, while finding second order cut sets, combination of segment A with other segments is not needed. Because the failure of A, alone causes the failure of network. It does not need combination of any other segment to cause failure of network.

To find second order cut sets, combinations list of 2 segments out of 8 segments is generated using WOLFRAM MATHEMATICA 10.1. Total number of combinations are found to be 28 and are listed in table.
3. Hence the new path matrix contains 5 rows (No. of paths) and 28 columns (No. of combinations of segments) and can be constructed as

\[
\begin{bmatrix}
A+B & B+C & B+F & C+D & D+E & D+G & D+H & E+F & G+H \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\
1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

(All the combinations with segment A are not needed and hence they are neglected. Dotted columns represent that there are few combinations that are not shown here because it's a large matrix and could not be fit to page.)

It can be observed that the elements in columns of matrix 4, representing combinations of \{B, C\}, \{B, F\}, \{D, G\} and \{D, H\} are all 1. It means that combined failure of these segments can cause failure of network and hence \{B, C\}, \{B, F\}, \{D, G\} and \{D, H\} are recorded as second order cut sets. Note that, while finding third order cut sets, any combination containing first order cut sets and second order cut sets are neglected. Because they don’t need more segments to cause failure of network.
Table 2 Hypothetical Network (Data and Results)

<table>
<thead>
<tr>
<th>Seg. No.</th>
<th>Comp.</th>
<th>Comp. Reliability</th>
<th>Weight</th>
<th>Relative Weight</th>
<th>Seg. Reliability</th>
<th>Probability of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Valve 1</td>
<td>0.9876</td>
<td>0.28</td>
<td>0.2979</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9876</td>
<td>0.28</td>
<td>0.2979</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Valve 1</td>
<td>0.9876</td>
<td>0.28</td>
<td>0.2240</td>
<td>0.989</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9876</td>
<td>0.28</td>
<td>0.2240</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Valve 1</td>
<td>0.9967</td>
<td>0.28</td>
<td>0.2188</td>
<td>0.993</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9956</td>
<td>0.31</td>
<td>0.2422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Valve 1</td>
<td>0.9900</td>
<td>0.28</td>
<td>0.2887</td>
<td>0.990</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9841</td>
<td>0.31</td>
<td>0.3196</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Valve 1</td>
<td>0.9945</td>
<td>0.28</td>
<td>0.2240</td>
<td>0.994</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9926</td>
<td>0.38</td>
<td>0.2969</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Valve 1</td>
<td>0.9851</td>
<td>0.28</td>
<td>0.2979</td>
<td>0.990</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9936</td>
<td>0.38</td>
<td>0.3918</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Valve 1</td>
<td>0.9900</td>
<td>0.28</td>
<td>0.2240</td>
<td>0.986</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9912</td>
<td>0.31</td>
<td>0.2480</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Valve 1</td>
<td>0.9778</td>
<td>0.31</td>
<td>0.2480</td>
<td>0.986</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>Valve 2</td>
<td>0.9827</td>
<td>0.31</td>
<td>0.3196</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Possible combinations of segments that can cause combined failure

<table>
<thead>
<tr>
<th>No. of segments to be combined</th>
<th>Possible Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{(A), (B), (C), (D), (E), (F), (G), (H)}</td>
</tr>
<tr>
<td>2</td>
<td>{(A, B, C), (A, D, E), (B, F, G), (A, H, B, C, D, E, F, G), (A, C, E), (A, C, F, A, C, G, A, C, H, A, D, E, A, D, F, A, D, G), (A, D, H), (A, E, F, A, E, G, A, E, H, A, F, G), (A, F, H), (A, G, H), (B, C, D, B, C, F), (B, C, G), (B, C, H), (B, D, E), (B, D, F), (B, D, G), (B, D, H), (B, E, F, B, E, G), (B, E, H), (B, F, G), (B, F, H), (B, G, H), (C, D, E), (C, D, F), (C, D, G), (C, D, H), (C, E, F), (C, E, G), (C, E, H), (C, F, G), (C, F, H), (C, G, H), (D, E, F), (D, E, G), (D, E, H), (D, F, G), (D, F, H), (D, G, H), (E, F, G), (E, F, H), (E, G, H), (F, G, H)}</td>
</tr>
</tbody>
</table>
Same procedure is repeated for finding third order cut sets with combinations list of 3 segments. Total number of combinations are found to be 56 as listed in table 3. Hence the new path matrix contains 5 rows (No. of paths) and 56 columns (No. of combinations of segments) and can be constructed as

\[
\begin{bmatrix}
A+B+C & B+C+D & B+D+F & B+D+G & B+E+G & B+E+H & C+D+E & D+E+F \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

As we can see, elements in columns of matrix 5, representing combinations of \{B, E, G\}, \{B, E, H\}, \{C, D, E\} and \{D, E, F\} are all 1, which means that the combined failure of these segments can cause failure of network and these are recorded as third order cut sets. The same procedure is repeated for each and every demand node in the network and all the cut sets are recorded. Note that any cut set is recorded only once. If the same cut set is identified while performing network analysis considering another demand node, it is not recorded as a cut set again.

Finally, the minimum cut sets after analyzing the network for all demand nodes are listed in table below.

<table>
<thead>
<tr>
<th>Order of cut sets</th>
<th>List of cut sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{A}</td>
</tr>
<tr>
<td>2</td>
<td>{B, C}, {B, F}, {D, G}, {D, H}, {C, F} and {G, H}</td>
</tr>
<tr>
<td>3</td>
<td>{B, D, E}, {B, E, G}, {B, E, H}, {C, D, E}, {C, E, H}, {C, F, G}, {D, E, F}, {E, F, H}, and {E, F, G}</td>
</tr>
</tbody>
</table>

Hence the reliability of the presented hypothetical network can be calculated as

\[
R_N = 1 - Q_N = 1 - \sum_{i=1}^{M} Q(MC_i)
\]

\[
Q_N = Q(MC_1) + Q(MC_2) + Q(MC_3) = 0.0107
\]

\[
\therefore R_N = 1 - Q_N = 0.9893
\]

5 CONCLUSIONS:

Mechanical failure of pipes in water distribution networks has been studied by numerous statistical models in the past. But none of these models focused on mechanical failure of other components of water distribution networks which may also affect the reliability of the whole network. This paper presents a methodology to evaluate mechanical reliability of water distribution networks along with its components, using minimum cut set method. The accuracy of a developed model depends on the accuracy of the data used to build it. The proposed model requires very detailed historic break data of all the components including pipes. But many municipalities are not equipped to collect such detailed data. In this paper, the failure rate of pipes is based only on a single parameter i.e., age of the pipe and the failure rate of other components is obtained using a more general formula. Consideration of as much parameters should lead to more realistic failure rate predictions. Research should be extended to also predict the failure rate of components other than pipe. Municipalities are required to collect detailed break data of all the components of water distribution networks. The availability of such data would assist in evaluating reliability more accurately.
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