Developing a simplified practical approach for analyzing the criticality of isolation valves

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Abstract

Maximizing reliability is imperative for water distribution networks (WDN) design. Recent claims about providing adequate and operable isolation valves as a focal aspect of a reliable WDN design have attracted substantial interest. In this direction, this paper attempts to answer the question of which isolation valves in a WDN must be prioritized based on their criticality towards enhancing WDN reliability. Two novel algorithms are proposed – one for ranking every isolation valve in a WDN and the second to identify the location of a new isolation valve to reduce the criticality of a specific valve in a WDN. Unlike the prevailing methodologies, the proposed algorithms are entirely based on the topological attributes of a WDN and do not require a calibrated hydraulic model, which is often a limiting factor in WDN management. Our proof-of-concept has unveiled the capability of the methodology to deliver preliminary information to water utilities regarding the criticality of valves without any hydraulic simulation.

Keywords

Isolation valve; Reliability; Design; Leakage; Water distribution system; Criticality

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INTRODUCTION

Classically, in water distribution network (WDN) analysis, the term reliability relates to the network's capability to achieve acceptable performance under both usual and unusual operating occasions (Xu and Goulter 1999). Maximizing reliability is often considered an imperative objective of WDN design. Nevertheless, there is no single agreed-upon description of reliability nor an exact procedure to estimate it. This has led to proposing a wide range of reliability indicators for WDN (Jayaram and Srinivasan 2008; Prasad and Park 2004; Tanyimboh and Templeman 1993; Todini 2000; Yazdi and Taji Elyatoo 2022). In a recent editorial, Walski (2020) reasoned that the commonly used surrogate indicators are only excess capacity indicators and are incorrect indicators of WDN reliability. As an alternative, Walski (2020) proposed two focal aspects for a reliable WDN design: "redundant, adequately sized piping, and intelligently sized and located storage" and "adequate, operable isolation valves, such that segments of the system that need to be shut down for maintenance such as pipe breaks, can be isolated to minimize their impact on the remainder of the network." This paper focuses on the second aspect as the first one, compared to the second, has received significantly more attention (yet less than it is needed) in the literature over the past few decades (Atkinson et al. 2014; Berardi et al. 2022; Ghesi et al. 2016; Gupta and Bhave 1994; Ostfeld and Shamir 1993; Prasad and Park 2004; T. et al. 2001; Xu and Goulter 1999).

Concerning the second aspect of adequate and operable isolation valves in WDN, the original thinking from a research perspective would be about locations for placing the isolation valves to minimize the shortfall caused by the need to isolate a pipe for maintenance or expansion (Jun 2005; Liu et al. 2017; Simone et al. 2022; Walski 1993a; b, 2011). The N rule (in which any demand node with N connecting pipes has N isolation valves towards each pipe) signifies the ideal
layout for isolation valve placement in a WDN from a hydraulic perspective. The N – 1 rule, with only N – 1 isolation valves towards N pipes connecting to every demand node, is a relaxed version of the N rule and can also serve as a standard layout for isolation valve placement in a WDN. However, from a practical viewpoint, these rules are redundant and expensive (Walski et al. 2006; Wéber et al. 2023). Nevertheless, surprisingly, from a detailed inspection of real-world WDN and a comprehensive review of design specifications of numerous water utilities worldwide concerning valve placing and spacing, it got revealed that the water utilities, more or less, follow (or are subject to follow) the N or the N – 1 rule.

Since isolation valves are not WDN components employed in daily operation, they are rarely maintained. In reality, many of them are inoperable when required for periodic closures due to a series of causes (Walski 2020). Therefore, in real-world WDN operation, isolation valves, if not adequately maintained, might induce substantial damage in terms of resilience or shortfall (Atashi et al. 2020; Beker and Kansal 2023). Several papers probing the vulnerability of the failure of isolation values toward identifying the most critical ones in a WDN can be found in the literature (Abdel-Mottaleb et al. 2022; Abdel-Mottaleb and Walski 2021; Creaco et al. 2012; Hernandez Hernandez and Ormsbee 2021; Liu et al. 2017; Trietsch and Vreeburg 2005; Wéber et al. 2023). The recent studies by Abdel-Mottaleb and Walski (2021) and Wéber et al. (2023) explored the use of graph theory to overcome the computational complexity of hydraulic simulations.

Nonetheless, most existing works following the segment-based approach (Walski 1993a) determine the critical segments rather than explicitly identifying the critical valves within a WDN. Though the concept of the critical segment accurately reflects the spatial distribution of the out-of-service WDN components during an isolation valve failure, it might not convey the essential information to the water utility operators about which isolation valve should be prioritized for
maintenance. Towards this direction, this paper proposes a straightforward methodology for ranking every critical isolation valve in a WDN. In addition to recognizing the critical valves in a WDN, a practical approach that enables the water utilities to detect the preferred location for a new isolation valve to reduce the criticality of a specific valve in a WDN is also proposed. Both methodologies use only the topology and demand data and no hydraulic simulations. Thus, the proposed algorithms will benefit many water utilities worldwide that struggle to maintain their assets and are unequipped with calibrated WDN hydraulic models. The proposed algorithms can successfully deliver preliminary information to water utilities regarding the criticality of valves that can be used for enhancing the overall reliability of WDN operation.

METHODOLOGY

Ranking critical isolation valves

The first algorithm (Algo-1) proposed for ranking the critical isolation valves in a WDN is depicted in Figure 1. It only uses the system topology data and node demands as input and does not involve any hydraulic simulation. Algo-1 can be partitioned into two stages. The first stage contains two loops: a loop for valves within a loop for the pipes. The algorithm is initiated by reading all the input data. Then it analyzes each pipe \((p \in P)\) individually and recognizes all valves required to isolate them. In other words, Algo-1 finds every segment within a WDN (Walski 1993a). After identifying the set of valves \((V_p,\) corresponding to every segment), the effect of the closure of pipe \(p\) on the shortfall in the nodes within the segment constituting pipe \(p\) is calculated and is stored as \(q_p\).

The algorithm then pans over to every valve \(v\) belonging to the set \(V_p\). It repetitively assumes the non-functioning of valve \(v\). Next, the new valves \(V_p^*\) needed to isolate the pipe \(p\) is
determined. In other words, the greater segment created by the failure of valve $v$ constituting the original segment is determined. The effect of the closure of pipe $p$ on the shortfall in the nodes within the greater (new) segment constituting pipe $p$ is assessed and is then saved as $q_p^\ast$. The $q_p^\ast$ value signifies the water unavailability damage caused by isolating pipe $p$ from the rest of the network under valve $v$, initially an element of the set $V_p$, being faulty. Later, $\Delta q_{v,p}$ is estimated as the difference between $q_p^\ast$ and $q_p$ values. After the $\Delta q_{v,p}$ values corresponding to every valve of the set $V_p$ are estimated, the algorithm then considers the next pipe of set $P$, and the process is repeated.

In the second stage, the algorithm looks at every valve $v$ in the WDN (belonging to the set $V$). It estimates the system shortfall caused by its malfunctioning, denoted as $\Delta q_v$. This value is estimated by totaling up the $\Delta q_{v,p}$ value for every pipe belonging to the set $P$ that gets isolated by closing valve $v$. Based on the $\Delta q_v$ values; the valves are ranked for criticality ($R_v$). Many valves may get the same rank value, and the minimum rank valve will not be the same as the length of the set $V$. The $R_v$ values calculated will be printed as the final output.

**Identifying new valve locations to reduce criticality**

Algo-2 proposed for identifying new isolation valve locations to reduce the criticality of the existing ones is depicted in Figure 2. As seen in Figure 2, the first stage of Algo-1 is incorporated into Algo-2. The algorithm starts by looking at every valve $v$ belonging to the set $V$. For each valve $v$, the set of pipes $P_v$, satisfying two conditions: having no valves on it and getting affected (isolated from the rest of the network) by its malfunction, is specified. The algorithm then pans over to each pipe $p$ belonging to the newly formed $P_v$. The steps performed in the first stage of Algo-1 are then performed and new rank values $R_p$ for pipes are established. Once the rank values are estimated
for every pipe $p$ belonging to set $P_v$ of every valve $v$, the pipe with the lowest rank ($R_p$ value) defined as $p^*$ is pinpointed as the best location for placing a new isolation valve to reduce the system shortfall caused by the failure of valve $v$. The new valve locations are finally printed as the output.

**Test network**

The test network considered is the C-Town WDN, one of the benchmark systems employed in WDN engineering research (Ostfeld et al. 2012). C-Town WDN consists of 429 pipes, 388 demand nodes, and 299 isolation valves. It may be noted that the isolation valves were not part of the original network input data, and they were added based on an analysis of the real-world data.

**RESULTS AND DISCUSSION**

**Identifying the most critical valve locations**

A straightforward instance (Figure 3) involving pipe P813 isolation is shown here to demonstrate the step-by-step process involved in the exercise using Algo-1. As seen in Figure 3a, three valves (V-P813, V-P811, and V-P840, belonging to the set $V_{p=P813}$) were found essential for isolating pipe P813 from the rest of the network, and they are denoted as A, B, and C, respectively. From isolating pipe P813, six demand nodes (J83, J311, J320, J321, J322, and J328) were found to be secluded from water accessibility, and the corresponding damage affected, implied as $q_{p=P813}$, was estimated as 5.18 L.s$^{-1}$. Each of the three valves (members of the original set $V_{p=P813}$) was then repetitively assumed as non-functional, and a different set of valves $V_{p^*P813}$ for isolating pipe P813 under the scenario of failure of valves V-P813, V-P811, and V-P840 was determined. The valves joined the set $V_{p^*P813}$ due to valve V-P813 (or valve A) failure were found as V-P228 and V-P815 (denoted as A1 and A2 in Figure 3a, respectively). Likewise, the valve that joined the set
Due to the failure of valve V-P813 (or valve A), and the resultant arrival of the situation to operate the valves V-P228 and V-P251 to isolate pipe P813, the damage affected, implied as $q_{v=V-P813,p=P813}$, was estimated as 0.17 L.s$^{-1}$. Similarly, due to the failure of valve V-P811 (or valve B) and the subsequent operation of valve V-P809, the resultant damage ($q_{v=V-P809,p=P813}$) was valued at 0.19 L.s$^{-1}$. Concerning the failure of valve V-P840, the accompanying value of $q_{v=V-P840,p=P813}$ was determined as 3.77 L.s$^{-1}$. As shown in Figure 3b, the non-functioning of the three valves belonging to the set $V_{p=P813}$ increased the damage associated with isolating pipe P813. For example, due to the failure of valve V-P840, the resultant damage induced increased to 8.95 L.s$^{-1}$ from the original value of 5.18 L.s$^{-1}$ (Figure 3b).

After individually analyzing each of the 429 pipes, the surplus demand values (surrogate of the damage), denoted by $\Delta q_v$, associated with the malfunctioning of the 299 existing isolation valves of the Test network, were evaluated. The $\Delta q_v$ values for the three valves (V-P813, V-P811, and V-P840) belonging to the set $V_{p=P813}$ were estimated as 1.15, 4.40, and 7.08 L.s$^{-1}$. Hence, out of the three valves, valve V-P840 (or valve C) was found to be the most critical one, and concerning the isolation of pipe P813, valve V-P840 must be put on top of the maintenance list. However, compared to the remaining existent valves, the $\Delta q_v$ value of valve V-P840 was found to be much inferior, and remarkably it was only ranked at 35. The ten most critical valves of the Test network are demarcated in Figure 4. The most critical valve ($R_v = 1$) is identified as V-P761 with a $\Delta q_v$
value = 28.31 L.s\(^{-1}\). Interestingly, the damage affected by the failure of V-P761 was found to be greater than one-tenth of the total average water delivered in the demand nodes of the Test network.

V-P340 was recognized as the isolation valve with the second-highest criticality (\(\Delta q_v = 23.70\) L.s\(^{-1}\) and \(R_v = 2\)).

Reducing the criticality of existing valves

Algo-2 was utilized to find the best locations for placing isolation valves within the WDN in the future to reduce the criticality of the existing ones. A simple illustration associated with lowering the criticality of valve V-P761 (Figure 5) is shown here to demonstrate the step-by-step process involved in the Algo-2 application. A single pipe link typically will have only one or two isolation valves placed. However, instances involving a change in pipe diameters, an unusual number of connections, unusually long links, necessity to place hydraulic control elements cause the placement of more than two or even more than three valves in a single pipe link. The network section in Figure 5 signifies such a location within the C-Town WDN.

The first step in the exercise was identifying the set of pipes \(P_v = V-P761\), with no valves attached to it, which gets isolated from the rest of the network by the breakdown of valve V-P761. These pipes are the eventual candidate for placing a new isolation valve for lowering the criticality of the existing valve V-P761. As seen in Figure 5, the region demarcated by blue specifies the greater segment generated by the malfunctioning of V-P761. Therefore, the pipes in this segment, specifically the ones with no isolation valves attached, constitute the set \(P_v = V-P761\).

Seven pipes – P-230, P-231, P-841, P-753, P-759, P-760, and P-808 – denoted as a, b, c, d, e, f, g, and h, respectively, were chosen as probable sites for placing an extra isolation valve. Algo-1 was applied to assess the damage caused by the failure of every potential isolation valve
belonging to the set $V_p$ of every pipe $p \in P_{v=P761}$. The seven pipes were ranked after examining the shortfall values (25.48, 20.23, 11.83, 7.20, 3.03, 15.25, and 15.57 L.s$^{-1}$, respectively). The pipe P-760 (or pipe f) that received the lowest damage value (3.03 L.s$^{-1}$) was assigned the rank $R_p = 7$ and got determined as the best location for placing a new isolation valve to reduce the criticality of valve V-P761.

Conclusions

This paper attempted to answer the question of which of all isolation valves in a WDN must be prioritized based on their criticality without performing any hydraulic simulations. Two novel algorithms using only the primary information of the network topology and nodal base demands were proposed: one for ranking every critical isolation valve in a WDN and the second to identify the location for a new isolation valve to reduce the criticality of a specific valve in a WDN. The pertinence of the two algorithms was demonstrated by applying them to a benchmark network. The first algorithm was employed to rank the criticality of the 299 existing isolation valves. The failure of the most critical isolation valve was estimated to induce water unavailability damage equivalent to greater than one-tenth of the total average water demand. The adjacent pipe to the most critical valve was identified as the best location for placing additional isolation valves to reduce the risk of failure of the most critical valve. Altogether, the case study results revealed the capability of the methodology to deliver preliminary information to water utilities regarding the criticality of values without using any well-calibrated hydraulic model. Furthermore, due to the simplicity of the proposed methodology, it will enable straightforward application. It can replace the approximate “thumb rules” commonly adopted by the water utilities and can assist them in systematically locating the valve locations within WDN.
Data availability statement

All data, models, or code generated or used during the study are available from the corresponding author by request.

Acknowledgement

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REFERENCES


LIST OF FIGURES

Figure 1. Schematic of Algo-1 for ranking the criticality of isolation valves.

Figure 2. Schematic of Algo-2 for identifying new valve locations.

Figure 3. (a) Valves to be operated for isolating pipe with ID P813 from the rest of the network and (b) the segments appended to the original segment during the failure of isolation valves with notations A, B, and C.

Figure 4. Top ten critical valves within the Test network.

Figure 5. Application of Algo-2 for selecting a future valve location to reduce the criticality of valve with ID V-P761.
Figure 1

START

INPUT
Network topology
Demand data

Stage 1

For every pipe
Determine the set of closest valves for isolating a pipe
Find the system shortfall

For each faulty valve
Determine the new set of closest valves to isolate a pipe
Find the new system shortfall
Find the surplus shortfall

Stage 2

Interpret the results
For every valve
Calculate the surplus shortfall associated with its malfunctioning
Rank the valves for criticality

OUTPUT
Valves ranking

END
Figure 2

START

INPUT

Network topology
Demand data
Algo-1 outputs

For every valve

Determine the set of pipes with no valves, affected by its failure

For each pipe

Calculate the new rank of pipe

Interpret the results

Identify the pipe with lowest rank value as the candidate to place a new valve

OUTPUT

New valve locations

END
INDEX

**Isolation valve**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Valve ID</th>
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<tbody>
<tr>
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<td>V-P761</td>
</tr>
<tr>
<td>2</td>
<td>V-P340</td>
</tr>
<tr>
<td>3</td>
<td>V-P789</td>
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<tr>
<td>4</td>
<td>V-P142</td>
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<tr>
<td>5a</td>
<td>V-P989</td>
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<tr>
<td>5b</td>
<td>V-P994</td>
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<td>V-P967</td>
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<tr>
<td>10</td>
<td>V-P995</td>
</tr>
</tbody>
</table>

**Note:** Notation 7 specifies valve V-P65 of rank seven.
Figure 5

INDEX

- Most critical valve
- Existing valve
- Possible future valve location
- Segment generated by the failure of valve V-P761