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DOI
10.1061/JWRMD5.WRENG-6505

Publication date
2024

Document Version
Final published version

Published in
Journal of Water Resources Planning and Management

Improving the Understanding of Secondary Impacts of Isolation Valve Closures on the Performance of Water Distribution Systems

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Abstract: Isolation valve closures (IVCs) can effectively assist pipe maintenance and management in water distribution systems (WDSs), but they inevitably cause secondary impacts on the WDS's performance. Previous studies have mainly focused on how to optimally operate or locate valves, but few efforts have been made on investigating the secondary impacts induced by IVCs. To this end, six quantitative metrics are proposed to comprehensively evaluate physical, hydraulic, and water quality impacts caused by IVCs. These metrics are used to explore how different network topologies, valve closing strategies, and valve placement strategies affect an IVC's overall impact on WDS performance. Applications to three real WDSs show the following: (1) the proposed metrics can effectively reveal underlying impacts caused by IVCs, especially the associated water quality risk that has rarely been considered before; (2) in addition to their surrounding pipes, IVCs can affect the water quality in pipes that are far away from the isolated segments; (3) a highly looped WDS is more likely to have higher water quality risk (e.g., due to flow direction reversal) but a lower hydraulic influence level (e.g., low pressure) compared to a WDS with many branched structures; and (4) while closing valves near the failed pipe is an overall strategy to reduce hydraulic impacts, it may also produce high water quality risk. The proposed metrics and the assessment framework are practically meaningful as they offer not only an improved understanding of the secondary impacts caused by IVCs, but also guidance for the decision-making process regarding valve maintenance and management. **DOI: 10.1061/JWRMD5.WRENG-6505.** © *2024 American Society of Civil Engineers.*

Author keywords: Isolation valve closures (IVCs); Water distribution system (WDS); Valve closure strategies; Valve placement strategy; Quantitative metrics.

Introduction

A water distribution system (WDS) is composed of various buried elements, including reservoirs, tanks, pipes, pumps, and valves. When these are designed and operated well, the system delivers the treated water from the plants to the end users in an effective and safe manner. Specifically, valves have been widely deployed in the WDSs, mainly aimed at isolating the pipes that need urgent repairs, replacement, cleaning, or disinfection. Therefore, isolation valves are important hydraulic elements of WDSs, and their operations can facilitate a good level of service to the users (Nikoloudi et al. 2021). This consequently leads to intensive efforts to conduct research on isolation valves in the WDSs.

The existing literature involving valves mainly focuses on two key aspects: (1) the design of the valve system, i.e., optimal placement of valves; and (2) planning valve operations during failure events (Jun and Loganathan 2007). The former aspect often involves the evaluation of sensitive and vulnerable areas in the WDS to guide the placement and maintenance of valves, including valve design for districted management area (DMA) partitioning (Creaco and Haidar 2019) and one-time or staged valve placement decisions (Lee and Jung 2021). This motivates the development of many multiobjective valve placement optimization algorithms (Liu et al. 2017; Yang et al. 2022). The research area of valve operations mainly involves the selection of valves that need to be closed to isolate a pipe segment (Abdel-Mottaleb and Walski 2021), the rapid identification of isolation segments (Liu et al. 2017), and avoidance of accidental isolation of pipes due to valve operation (Jeong et al. 2021).

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Note. This manuscript was submitted on November 27, 2023; approved on February 12, 2024; published online on May 16, 2024. Discussion period open until October 16, 2024; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

In addition to the research progress on valve system design and operations, many researchers have been engaged in valve system performance evaluation using either hydraulic simulation (Creaco and Walski 2017; Do et al. 2018) or mathematical modeling such as graph theory (Giustolisi and Savic 2010). The former uses a hydraulic model to analyze the performance of the valve system, with indicators including the volume of leakage (Creaco and Pezzinga 2015), fire protection requirement compliance (Hernandez Hernandez and Ormsbee 2021), and layout costs (Alvisi et al. 2011; Creaco and Pezzinga 2015). The graph theory-based methods include matrix-based approaches (Giustolisi and Savic 2010), complex network theory (Giustolisi et al. 2022), and system segment diagrams (Wéber et al. 2020). Those methods eliminate the need for a hydraulic simulation model to achieve rapid performance evaluation on the valve system. Examples of the main evaluation indicators include the configuration properties, isolation segment size, and valve density (Walski 1993; Zischg et al. 2019; Hwangs and Lansey 2021; Simone et al. 2022).

Even with the aforementioned considerable efforts in the development of valve design and operation methods, there is a paucity of studies focusing on the impacts of isolation valve closures (IVCs) on the performance of the WDSs. Although timely valve closure after pipe failure limits the extent of adverse conditions and avoids further deterioration of the situation, it still takes time before the WDS returns to normal operation. Therefore, the impact of closing valves on the WDS is directly related to how the water supply company takes subsequent remedial actions, which is important to ensure the continuity of supply. In other words, while isolation valve closures (IVCs) can effectively assist pipe maintenance and management in the WDSs, they inevitably cause secondary impacts on the WDS's performance, such as low pressure or shortage of water supply (Nikoloudi et al. 2022). However, to the best of our knowledge, an understanding of the impacts of IVCs on WDS performance is still insufficient.

Some previous studies have been conducted to address this issue. For example, Walski (1993) was the first to propose the concept of segments, defined as the smallest part of the distribution system that can be isolated by closing valves. Subsequently, based on the concept of segments, various aspects of IVCs have been explored, such as the hydraulic impacts of IVCs on the WDSs (Walski et al. 2006), valve importance assessment (Walski et al. 2019), and cost control (Meng et al. 2019). These studies laid a solid foundation for subsequent studies on the impact of IVCs. In recent years, Nikoloudi et al. (2021, 2022) have developed a new biobjective optimization method to identify the optimal valve operations (the operation interventions and the starting time) using the metrics of water supply interruptions, low pressure impacts, and discoloration risk increase. In addition, Beker and Kansal (2023) conducted a study on the impacts of IVCs on the WDS under different valve placement strategies based on the number of closed valves, the number of people affected, and the supply shortfall.

However, these studies do not provide a comprehensive assessment of WDS performance change under IVCs. Specifically, while the studies conducted by Walski (1993) as well as Beker and Kansal (2023) consider many different hydraulic impact aspects and IVC scenarios, water quality metrics are not involved in their study. While the discoloration risk used in Nikoloudi et al. (2021) represents an aspect of water quality risk, it is not straightforward to enable the calculation. More importantly, only a single failure event is considered in most of these studies (Walski et al. 2019; Nikoloudi et al. 2021, 2022), which significantly differs from the present study in that a very large number of failure scenarios are accounted for to comprehensively assess the overall impacts of IVCs on the WDS's performance. In conclusion, to comprehensively analyze the impact of IVCs on the WDS, both aspects must be considered simultaneously: one is to consider all pipeline failure scenarios that may occur within the WDS, and the other is to consider multiple evaluation metrics that include physical hydraulic and water quality impacts. This forms as the knowledge gap in current literature and applications.

To address the above gap, this paper proposes a new framework for a comprehensive assessment of the secondary impact of isolation valve closures (IVCs) on WDS performance. The proposed framework makes use of a set of metrics that allow simultaneously assessing physical impacts (i.e., the number of closed valves and the length of pipes in the isolated segments), hydraulic impacts (i.e., the length of the affected pipes and the number of affected people), and water quality impacts (i.e., the length of pipes with affected flow directions and velocities). The main contributions and novelties of this study include (1) the proposal of a comprehensive set of metrics to quantitatively measure the secondary impacts induced by IVCs on WDS performance, where two water quality metrics of flow direction reversal and sudden velocity changes under IVCs are first considered; (2) the development of a new application framework to systematically assess the overall influences caused by IVCs on the WDS performance under a wide range of pipe failure scenarios with the aid of the proposed metrics; and (3) an attempt to explore how different network topologies, valve closure strategies, and valve placement strategies affect the secondary impacts associated with IVCs. It is anticipated that the proposed metrics and framework offer insights into the underlying relationships between the WDS performance and IVCs, thereby providing important guidance for the management, maintenance, and operation of valves in WDSs.

This paper is organized as follows. The proposed methodology is first described, where the performance metrics and the proposed application framework are presented. This is followed by the descriptions of case studies, and then the results and discussions are presented. Finally, the "Conclusion" section summarizes the main findings and implications of this study.

Methodology

The proposed research methodology and application procedure are presented in Fig. 1. First, a total of six metrics is defined based on three aspects, in order to reveal the underlying impacts of isolation valve closures (IVCs) on WDS performance. These include the physical impact, hydraulic impact, and water quality impact. In addition, a comprehensive metric is proposed to simultaneously consider all of the above three aspects. Second, a framework is developed to assess the impacts of IVCs on WDS performance with the aid of a pressure-driven model. This model is used to generate pipe failure scenarios, as well as to identify the valves that need to be closed in order to isolate the failed pipes. In addition, the pressure-driven model is employed to compute the hydraulics of the WDS in order to calculate the values of different metrics. Finally, the effects of IVCs on WDS performance are explored under different WDS topologies, valve closure strategies, and different valve placement strategies with the aid of the proposed metrics and assessment framework. Details of each stage of the proposed methodology are given in the subsequent subsections.

Performance Metrics

In this study, six quantitative metrics are proposed to characterize the impact of IVCs on WDS's performance, with each emphasizing a particular aspect of this impact. More specifically, physical impacts are represented by the metrics of the number of closed valves

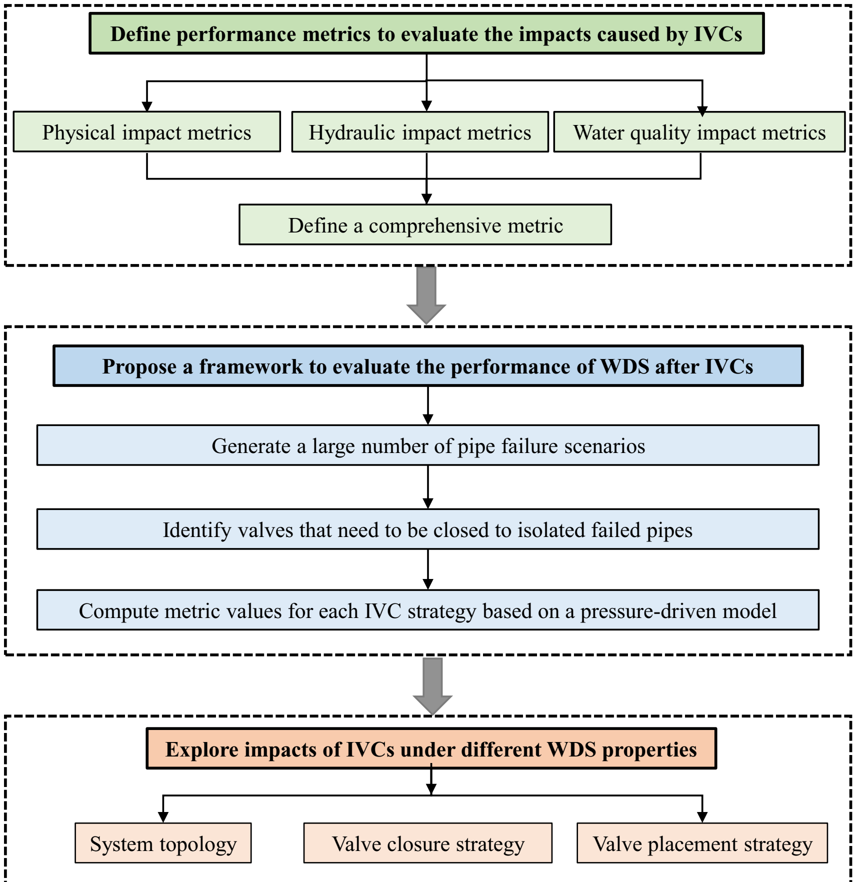

Fig. 1. Proposed research methodology.

and the length of pipes in the isolated segments; hydraulic impacts are measured by the metrics of the length of the affected pipes and the number of affected people; and water quality impacts are reflected by the metrics of the length of pipes with inversed flow directions and the length of pipes with sudden velocity changes. In practical implementations, well-calibrated hydraulic models can be used to measure pipe flow velocity and direction changes by comparing these parameter values before and after isolation valve operations. It is noted that these flow property variations do not necessarily result in water quality problems, and it is challenging to specify a criterion for a real system. However, the sudden flow velocity and direction changes can increase water quality risks due to the presence of disturbed sediment and biofilm in the pipes, which should be considered within the IVCs. Note that the metrics of the length of affected pipes, the length of pipes with inversed flow directions, and the length of pipes with sudden velocity changes consider only the pipes outside the isolated segments. These six metrics all use peak hour demand for simulation (snapshot simulations) to consider the largest possible impacts caused by IVCs. Details of the proposed metrics are presented below.

Number of Closed Valves

When a pipe j failure occurs, it is necessary to close the nearest valve(s) to completely isolate this failed pipe to facilitate subsequent maintenance work (Liu et al. 2017; Hernandez Hernandez and Ormsbee 2022). Therefore, it is straightforward to define the metric of the number of closed valves (Ω_j^C) to evaluate the performance of the valve systems (Beker and Kansal 2023). More specifically, a greater value of Ω_j^C indicates that a larger number of valves needs to be closed in order to isolate the failed pipe j, implying a relatively low performance level. This is because operating a larger number of valves may require additional time and labor efforts, and more importantly may produce larger impacts on WDS performance. Ideally, two valves installed at both ends of a pipe can produce a very low Ω_j^C value, but unfortunately this is unrealistic due to the high purchase and maintenance costs associated with valves (Creaco and Pezzinga 2015). In addition, in engineering practice, many existing valves cannot be operated as they are often in disrepair, especially in many developing countries. Consequently, a lower value of Ω_j^C is deserved.

Length of Pipes in the Isolated Segment

Closing the valve can cut off the connection between the failed pipe and the surrounding pipes, forming an isolated water-stop area (often referred to as an isolated segment). The length of pipes in the isolated segment regarding the failed pipe j can be defined as

$$IA_j = \sum_{k \in \Omega_j^I} L_k \tag{1}$$

where IA_j = total length of pipes in the isolated segment; Ω_j^I = set of pipes within the isolated segment; and L_k = length of pipe k.

Length of Affected Pipes Outside the Isolated Segment

In addition to physical impacts measured by Ω_j^C and IA_j, valve closures can cause large hydraulic influences on the WDS performance. More specifically, IVCs may cause a pressure drop or even negative pressure at some pipes outside the isolated segment, which can accordingly affect water supply security. The affected pipes outside the isolated segment may consist of two parts, one being the outage segments (Walski et al. 2006) that are located downstream of the isolated segments, and the other being the affected upstream segments near the isolated segments. Therefore, it is highly important to identify the pipe with pressure fluctuations as a result of IVCs, where the pressure calculation is obtained by a pressure-driven model. This metric can be mathematically described as

$$AH_j = \sum_{k \in \Omega_j^H} L_k \tag{2}$$

where AH_j = total length of affected pipes outside the isolated segment due to IVCs that are used to isolate the failed pipe j; and Ω_j^H = set of pipes whose pressure is below the required pressure due to the IVCs, which can be expressed as follows:

$$\Omega_j^H = \{k | H_k^u(j) < H^{req} \text{ or } H_k^d(j) < H^{req}, k = 1, 2, \ldots, M\} \tag{3}$$

where $H_k^u(j)$ = pressure at the upstream node of pipe k ($k = 1, 2, \ldots, M$, M is the total number of pipes); $H_k^d(j)$ = pressure at the downstream node of pipe k; and H^{req} = required pressure value used to deliver the sufficient water amount.

Number of Affected People

Hydraulic impacts induced by IVCs can also be measured by the number of people with insufficient water supply. This metric can be defined as follows:

$$AP_j = \sum_{i \in \Omega_j^Q} P_i \tag{4}$$

where AP_j = number of affected people caused by IVCs used to isolate pipe j; P_i = number of people associated with demand node i; and Ω_j^Q = set of demand nodes whose water supply is affected by IVCs. In engineering practice, if the amount of supplied water drops below a certain level, the daily life of the users is affected. For instance, in China, when the amount of water supply is below $r = 70\%$ of the designed or required amount, the user would complain with a high likelihood. Therefore, Ω_j^Q can be expressed as follows:

$$\Omega_j^Q = \left\{ i \middle| \int_0^T Q_i^j(t)dt < r \int_0^T Q_i^{req}(t)dt, i = 1, 2, \ldots, N \right\} \tag{5}$$

where $Q_i^j(t)$ = amount of water supplied to node i ($i = 1, 2, \ldots, N$, N is the total number of nodes with demand users) at time t after IVCs; T = time period from the start of valve closures to the status with normal water supply (i.e., the reopen of the closed valves); $T = 1$ h is used in this study based on the assumption that valve isolation duration is typically within 1 h (Qi et al. 2018a); $Q_i^{req}(t)$ = water demand level required by node i at time t before IVCs; r = ratio between the actual and required water supply amount; and $r = 0.7$ is used in this study to enable the illustration and analysis.

Length of Pipes with Inversed Flow Directions

The reverse flow in pipes with predominant flow directions, except for those whose flow direction changes within their normal operations, is likely to cause water quality problems due to the presence of disturbed sediment and biofilm in the pipes and related shear stress and/or velocity increases (LeChevallier 1990; Kowalski et al. 2010; Abraham et al. 2018; Qi et al. 2018b). On this basis, the present study proposes a metric of the length of pipe with inversed flow direction after IVCs, in order to measure the water quality impacts. Note that this metric only considers pipes with a fixed flow direction during normal operation, which does not include pipes that change flow directions frequently due to water demand or boundary conditions. This proposed metric is defined as follows:

$$AD_j = \sum_{k \in \Omega_j^D} L_k \tag{6}$$

where AD_j = length of the pipes with reverse flow directions outside the isolated segment; and L_k = length of pipe k, which is taken from the set of pipes with changed flow directions Ω_j^D. More specifically, all pipes with changed flow directions after ICVs are assigned to Ω_j^D.

Length of Pipes with Affected Flow Velocities

The valve closures can significantly change the flow paths of some pipes in the WDS, and hence the flow rate of some pipes may increase suddenly (Donlan and Pipes 1988; Colombo and Karney 2002; Lehtola et al. 2006). This can scour the pipe wall and accordingly result in high water quality risk. Therefore, it is important to take this secondary impact into account, with its equation given below:

$$AV_j = \sum_{k \in \Omega_j^V} L_k \tag{7}$$

where AV_j = length of pipes with large velocity increases outside the isolated segment; and Ω_j^V = set of pipes with large velocity increases, which can be expressed as follows:

$$\Omega_j^V = \{k | V_k^A(j) \geq \varphi V_k^O(j), k = 1, 2, \ldots, M\} \tag{8}$$

where $V_k^A(j)$ = flow velocity in pipe k after IVCs that are used to isolate pipe j; $V_k^O(j)$ = flow velocity in pipe k before IVCs; and φ = user-specified parameter ($\varphi > 1$) representing the velocity increase threshold related to the peak velocity of a pipe. In this study, $\varphi = 1.5$ is used for the case studies by following our previous work of Qi et al. (2018b).

It is noted that each of these six metrics can be used to describe the results for a particular pipe failure scenario j. In this study, the mean values of all possible pipe failure scenarios are used to represent the overall performance of the valve system in the entire WDS (i.e., a large number of IVC scenarios) under a certain metric, which can be defined as follows:

$$f = \frac{1}{J} \sum_{j=1}^{J} f_j \tag{9}$$

where $f_j = \Omega_j^C$, IA_j, AH_j, AP_j, AD_j, or AV_j; $f = \Omega^C$, IA, AH, AP, AD, or AV; J = total number of pipe failure scenarios; $J = 1$ when a single pipe failure scenario is considered; and $J = M$ when each pipe of the entire WDS is considered as a failure scenario.

Comprehensive Performance Metric

The means of the six performance metrics described above, i.e., Ω^C, IA, AH, AP, AD, and AV represent different aspects of WDS performance after IVCs. To account for the overall impacts of all these different performance aspects, a comprehensive performance metric R is defined as follows:

$$R = \frac{\sum_{i=1}^{I} \alpha_i rank(R(f))}{\sum_{i=1}^{I} \alpha_i} \tag{10}$$

where $rank(R(f))$ = ranking value of each metric f ($f = \Omega^C$, IA, AH, AP, AD, or AV), with a lower value representing a higher rank; I = total number of metrics considered, and hence $I = 6$ in this study; and α_i = weight of each metric, which can be assigned different values according to project priorities in applications. Taking the metric of IA as an example, there are three different valve closure strategies for an example WDS. These strategies produce metric IA values of 1.3 km, 1 km, and 1.5 km, respectively. As a result, the ranking results, i.e., $rank(R(IA))$, of these three strategies based on metric IA are 2, 1, and 3, respectively. By weighting the average of the results obtained from the six metrics, the secondary impact of valve closure on the WDS can be comprehensively evaluated. As shown in Eq. (10), R represents the weighted average of all metric rankings, and the valve system with the lowest R metric value has the lowest rank value [i.e., $rank(R(f)) = 1$], representing the lowest impacts of the ICVs on WDS performance.

In this paper, the weight of each metric is set to $\alpha_i = 1$ for all analyzed cases, indicating that the impact of each metric is equally considered. In actual application, the values of α_i can be set to different values when some metric(s) need(s) to be focused on. For instance, the weight α of the length of pipes in the isolated segment metric can be weighted much higher than the other objectives if the primary purpose is to isolate segments for maintenance. On the other hand, the weights of metrics of the length of pipes with inversed flow directions and with affected flow velocities can be set higher if the main focus is to maintain normal water quality outside the isolated segments.

It is noted that the rank values adopted in Eq. (10) are used to unify the measurement standard across different performance metrics that possess different dimensions and value ranges. The R value represents the ranking of a certain valve system among all alternatives measured by the secondary impacts caused by IVCs. A lower R value indicates that the ICVs cause less performance degradation of WDS.

Proposed Framework to Assess the Impacts of IVCs

Pressure-Driven Model

The pressure-driven model is used to enable the hydraulic analysis for the WDS under IVCs. This is because the pressure-driven model has significant advantages in simulating the actual hydraulic conditions in WDS when valves are closed. It can accurately reflect the changes in pressure, water delivery volume, flow direction, and flow velocity in WDS. The pressure-driven model is given as follows (Qi et al. 2018b):

$$Q_i = Q_i^{req}\left(\frac{H_i - H_i^{\min}}{H_i^{req} - H_i^{\min}}\right)^{\mu} \quad H_i^{\min} \le H_i \le H_i^{req} \tag{11}$$

where Q_i = actual water delivered to node i; and Q_i^{req} and H_i^{req} = required nodal demand and pressure, respectively. For the case studies considered in this paper, the minimum pressure required to deliver the specified demands (H^{req}) is set equal to 18 m for each demand node. When pressure falls below this value, the pipe is considered to be affected by the induced IVCs. Both requirements have to be satisfied to meet the desired service level. H_i is the actual nodal pressure, and $H_i^{\min}$ is the minimum pressure allowed, below which no water can be supplied to the node (usually $H_i^{\min} = 0$). μ is the pressure exponent, which often takes a constant of 0.5 as recommended by the previous works (Qi et al. 2018b).

In this study, a total of M scenarios is considered to enable the impact analysis induced by IVCs, where M is the number of pipes in the WDS. For each scenario, assuming that only one pipe needs to be isolated using valves, it is noted that the pressure-driven model can be used to identify affected customers (Walski et al. 2006), but in this study this model is used to enable hydraulic analysis of WDSs under IVCs.

Method to Identify the Valves That Need to be Closed for Pipe Isolation

After a pipe failure occurs, it is typical to close the nearest valve to cut off the connection between the failed pipe and the water source. Much of the literature assumed that valves are available at both ends of the failed pipe (Shuang et al. 2014; He and Yuan 2019; Balekelayi and Tesfamariam 2019), and hence the simulation assumes that a single pipe needs to be isolated. This assumption is unrealistic because in many cases a limited number of valves is installed in a WDS (Walski 1993; Giustolisi and Savic 2010; Beker and Kansal 2023). Therefore, these investigations based on the one-to-one correspondence between pipes and valves can be misleading when applied to realistic cases. To analyze the impacts of IVCs on WDS performance, it is necessary to identify the number and location of valves that need to be closed based on the location of the failed pipes, which may be achieved through the segment identification method proposed by Walski et al. (2006).

Similar to the study of segment identification by Walski et al. (2006), this study proposes a method to identify valve closure plans based on graph theory. It is noted that this method is proposed and applied for the identification of isolation valves, but not for check valves. First, based on the topological relationship in the WDS, the adjacency matrix between nodes and pipes is developed as follows:

$$\boldsymbol{A}_{(i,j)} = \begin{array}{c} J_1 \\ J_2 \\ J_3 \\ J_4 \\ J_5 \\ J_6 \\ \vdots \\ J_n \\ \\ \end{array} \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & \ldots \\ -1 & 0 & 0 & 0 & 0 & \ldots & 0 & 1 & 0 & 0 & \ldots \\ 0 & -1 & 0 & 1 & 1 & \ldots & 0 & 0 & 0 & 0 & \ldots \\ 0 & 0 & -1 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & \ldots \\ 0 & 0 & 0 & -1 & 0 & \ldots & 0 & 0 & 1 & 0 & \ldots \\ 0 & 0 & 0 & 0 & -1 & \ldots & 0 & 0 & 0 & 1 & \ldots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \ldots & -1 & 0 & 0 & 0 & \ldots \end{bmatrix} \\ \qquad\qquad P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5 \quad \ldots \quad P_u \quad P_{v1} \; P_{v2} \; P_{v3} \; \ldots \tag{12}$$

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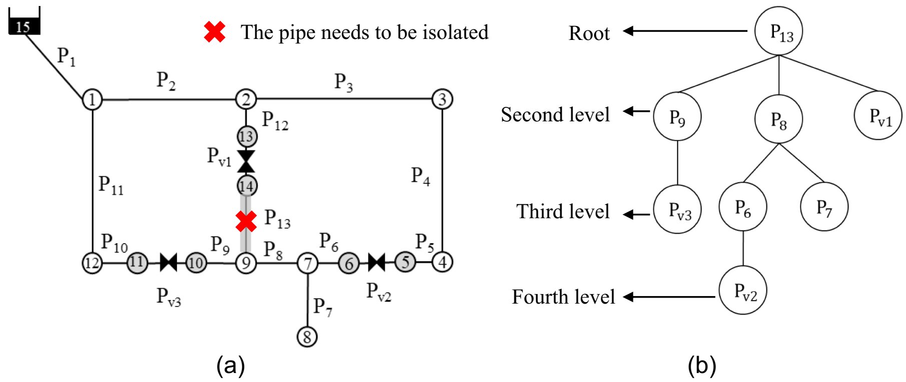

Fig. 2. Illustration of the proposed method to identify valves to isolate a pipe: (a) WDS with an accident pipe; and (b) multiway tree traversal calculation process.

where $\mathbf{A}_{(i,j)}$ = adjacency matrix representing the connection relationship between nodes and pipes in the WDS, which can be divided into two matrices, $\mathbf{A}^{u}_{(i,j)}$ [left side of the dotted line of Eq. (12)] and $\mathbf{A}^{v}_{(i,j)}$ [right side of the dotted line of Eq. (12)]. $\mathbf{A}^{u}_{(i,j)}$ represents nodes connected to nonvalve pipe sections, while $\mathbf{A}^{v}_{(i,j)}$ represents nodes connected to valve pipe sections. The rows and columns of the matrix represent nodes and pipes, respectively. Next, according to the established matrix, the pipe connection equation can be formulated as follows:

$$\boldsymbol{C}_j = |\boldsymbol{A}^{T}_{(*,j)}||\boldsymbol{A}_{(i,j)}| \tag{13}$$

where $\mathbf{C}_j$ = relationship between any pipe and pipe j; and $\mathbf{A}^{T}_{(*,j)}$ = N-dimensional column vector composed of elements in the jth column of the adjacency matrix. There are three possibilities for the result of $\mathbf{C}_j$, $\mathbf{C}_j = 0$ if the pipe is not connected to pipe j, $\mathbf{C}_j =$ 1 if it is connected to pipe j, and $\mathbf{C}_j = 2$ if it is pipe j itself. Finally, a multiway tree data structure is established with the failed pipe j as a root and the valves that need to be operated as the leaves. The isolated segment is then identified through the multiway tree traversal algorithm, followed by the identification of the set of closed valves Ω^{C}_{j} and the set of pipes within the isolated segment Ω^{I}_{j} for the failed pipe j.

Take a WDS with a failed pipe as an example, as shown in Fig. 2(a), where pipe 13 (P_{13}) needs to be isolated for maintenance. Through the graph theory mentioned by Walski (1993) and multiway tree traversal algorithm, it can be seen from Fig. 2(b) that after the failure of P_{13}, three valves need to be closed, namely P_{v1}, P_{v2}, and P_{v3}, and the pipes in the isolation segment are P_6, P_7, P_8, P_9, and P_{13}. Therefore, in this example, $\Omega^{C}_{P_{13}} = \{P_{v1}, P_{v2}, P_{v3}\}$, $\Omega^{I}_{P_{13}} = \{P_6, P_7, P_8, P_9, P_{13}\}$.

Relationship between WDS Properties and Impacts Induced by IVCs

The framework proposed in this study is used to explore how different WDS properties affect secondary impacts on the WDS induced by IVCs. These properties include different WDS system structures, valve closure strategies, and valve placement strategies. More specifically, the aim is to understand the underlying relationship between different WDS topologies (looped and branched) and the secondary impacts on WDS performance caused by IVCs. In addition, an attempt is made to improve the understanding of how different valve closure and placement strategies influence the secondary impacts of the IVCs on WDS's physical, hydraulic, and water quality performance.

Case Studies

Descriptions of Case Studies

In this study, the proposed method is applied to three case studies, which are two district meter areas (i.e., DMA1 and DMA2) of the same WDS and the full-size network of a real-world WDS, the Jiaxing Network (JXN) in China. The real-world JXN case study is representative of common situations found in WDSs of most cities in China. The three cases are shown in Fig. 3 with corresponding specific information given in Table 1. As can be seen from this table, the length of most pipes can be longer than 1 km, while the number of valves is limited. As a result, the segment lengths in these WDSs may exceed 5 km (e.g., with a five-pipe segment), which is much longer than what is common in developed countries (Walski 2011). In addition, as shown in Fig. 3, in these three real cases from China, the isolation valve layout at a pipe intersection does not follow the N or $N-1$ rule (herein N is the number of pipe branches at the intersection), which is very different from the isolation valve arrangements in developed countries (e.g., as studied in Walski 2002; Walski et al. 2006).

To simulate the WDS hydraulics behaviors of these three cases under the IVCs, the pressure-driven model EPANET2.2 (Rossman 1994) is used. Note that although EPANET is the widely used model in the world, it has some limitations in terms of demand allocation. For example, a demand may be assigned only to a network node, but because of valve location, it may be located in a segment not containing that node. This can be overcome by introducing additional nodes with demands, especially along longer pipes, although this will increase the overall computational time. Note that some commercial software overcomes this issue by accounting for the exact location of customer connections (when such data are available) so that the customer is assigned to the correct segment. Moreover, in order to consider the maximum impact of IVCs on WDS performance, a peak-hour demand scenario (i.e., the hour of the day with the highest demands) is used as an operational scenario for all case studies. Such an analysis is practically meaningful as isolation valve closure, and their reopening is often performed in a relatively short time period due to the rapid development in pipe operation and maintenance technology (Qi et al. 2018a). We assume that after a pipe failure occurs, the nearest valves are identified using

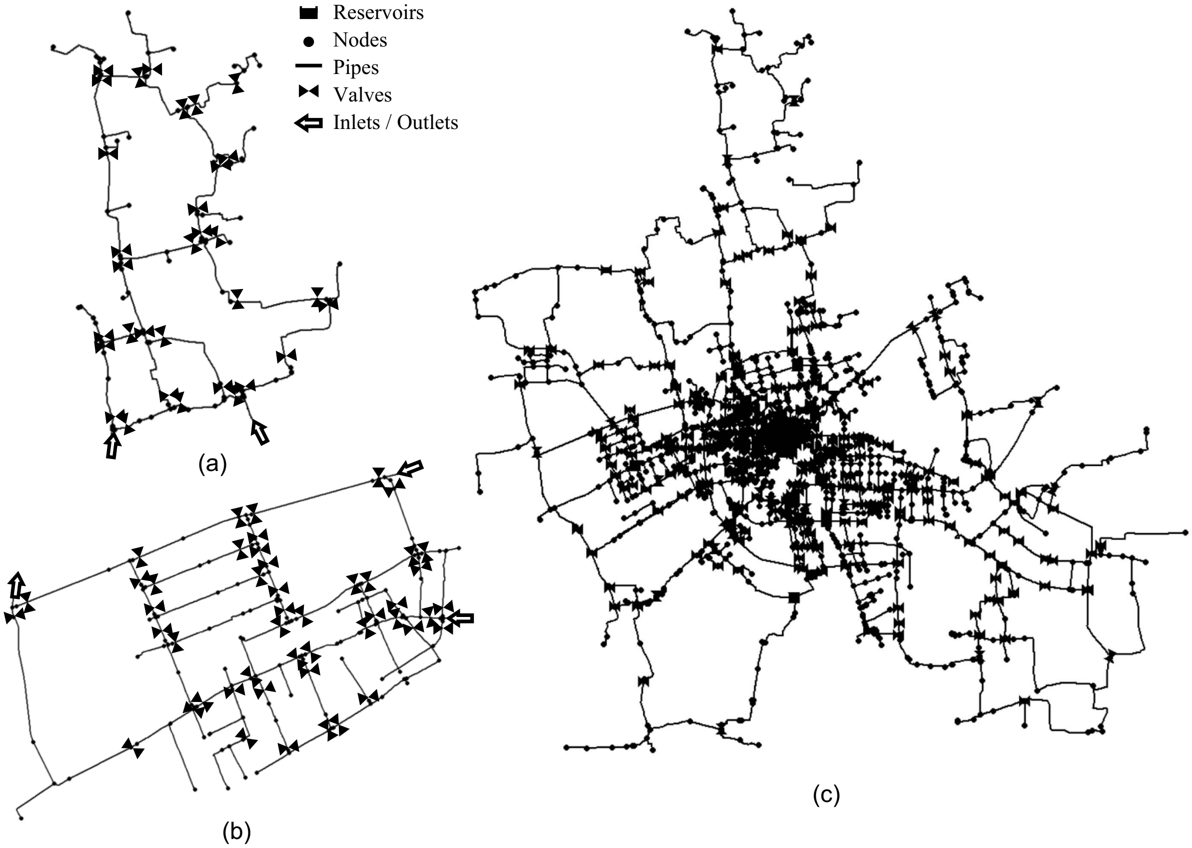

Fig. 3. Layouts of the WDS with valves: (a) DMA1; (b) DMA2; and (c) JXN.

Table 1. Case information

Items	DMA1	DMA2	JXN
Number of supply reservoirs/water inlet pipes	2	2	5
Number of water outlet pipes	0	1	0
Number of valves	32	51	475
Number of demand nodes	140	209	2,621
Number of pipes	113	171	2,543
Total length of pipes	70.80 km	58.66 km	838.55 km

the isolated segment identification method, where their closures immediately form an isolation zone.

Discussion of the Parameter φ of the Length of Pipes with Affected Flow Velocities Metric

In order to study the effect of the selected φ value on the simulation results, different parameter values of φ (1.2, 1.5, 1.8, 2.0, 2,2, 2,5) are tested for the studied system, and the results are shown in Fig. 4. As expected from this sensitivity analysis, different parameter values lead to different simulation results. To be specific, higher parameter values result in shorter lengths of pipes with affected flow velocities. For instance, when the value of φ changes from 1.2 to 1.8, the obtained AV value decreases from 14.82 km to 7.79 km, as shown in Figs. 4(a and c). As a result, in actual applications, different parameter values can be selected according to different characteristics of the pipe network. For example, in a WDS with low peak flow velocities, the value of φ may be set relatively low, because there is a lack of flushing in these pipes that usually leads to more sediments. Consequently, a small increase in flow velocity may induce significant changes in water quality. However, the setting of φ is dependent on many practical factors, which is not the focus of this study, so $\varphi = 1.5$ is used as was done in Qi et al. (2018b).

Results and Discussion

Impacts of IVCs on WDS Performance under Different System Topologies

The proposed method is first applied to the two small WDSs (DMA1 and DMA2) to explore the impacts of isolation valve closures (IVCs) on WDS performance under different system topologies. The valve-to-pipe ratios for DMA1 and DMA2 are 0.28 and 0.29, respectively, indicating that the average numbers of valves per pipe are similar in these two cases. Therefore, it is meaningful to compare these two cases, which, in turn, enables us to explore the similarities and differences in the secondary effects of valve isolation in WDSs with different structures. In this section, each failed pipe is isolated by closing the nearest valves, and Fig. 5 shows the statistical distribution of the resultant six metric values for DMA1 and DMA2. In order to fairly compare the two cases, the results were normalized accordingly. More specifically, the metrics expressing the length of pipes in the isolated area, the length of affected pipes outside the isolated area, the length of pipes with inversed flow directions, and the length of pipes with affected flow velocities were all divided by the total length of the respective WDSs. In addition, the metric based on the number of affected people is also divided by the total population served by its WDS.

J. Water Resour. Plann. Manage., 2024, 150(8): 04024023

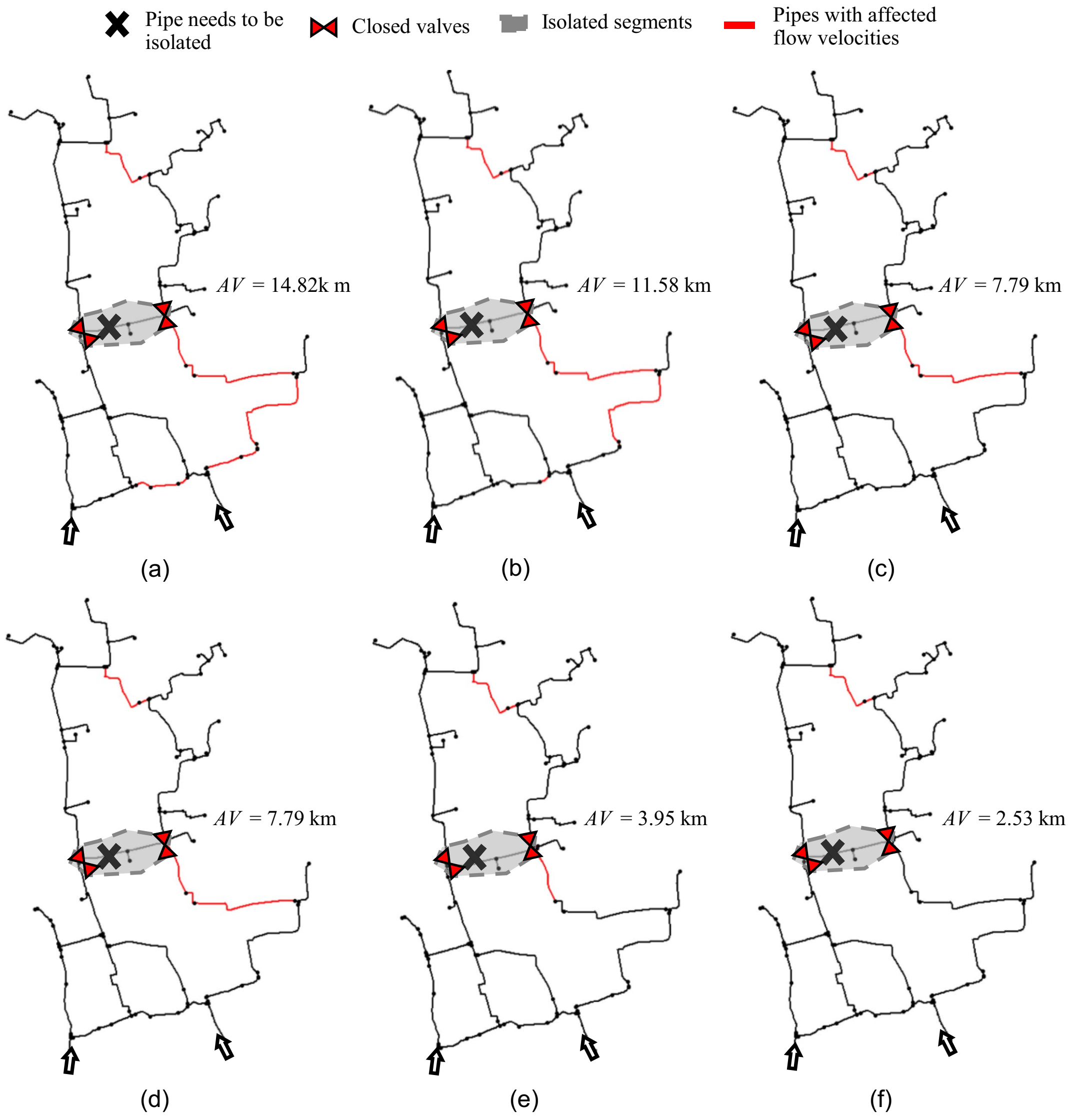

Fig. 4. Results of the length of pipes with affected flow velocities (metric AV) under different values of φ: (a) $\varphi = 1.2$; (b) $\varphi = 1.5$; (c) $\varphi = 1.8$; (d) $\varphi = 2.0$; (e) $\varphi = 2.2$; and (f) $\varphi = 2.5$.

As shown in Fig. 5(a), DMA1 needs to close up to three valves to isolate the failed pipe from other segments, while the DMA2 requires to shut off up to five valves. The average number of closed valves for pipe failures in DMA1 is lower than that in DMA2 due to the fact that the latter possesses many looped structures (see Fig. 3). In addition, it can be seen from Fig. 5(b) that the average ratios of the pipe length in the isolated segment for DMA1 and DMA2 account for about 3.5% and 2.6% of the total length of each WDS, respectively. These length values are relatively large compared to the total length of the pipes, indicating a low density or suboptimal placement of valves within these two DMAs.

Regarding hydraulic impacts as shown in Fig. 5(c), the ratio of the affected pipe length outside the isolated segment (AP) under IVCs is much larger for DMA1 than for DMA2. This is as expected, as DMA2 has a larger number of looped pipes, which offer more water delivery paths compared to DMA1. As shown in Fig. 5(d), the people affected by the water shortage of the two DMAs are located mainly inside the isolated segment. Furthermore, it is observed that compared with DMA1, the mean and peak values of the ratio of affected people for DMA2 are much higher than those for DMA1. The reason for this phenomenon is that DMA2 is located in a densely populated area, and many nodes in DMA2 serve a larger population size than DMA1, so its impact is greater when demand nodes are short of water.

As for water quality impacts, the maximum and average values of the ratio of pipe length with flow direction change and velocity increase for DMA2 are slightly larger than those of DMA1 as can be seen from Figs. 5(e and f). This is because DMA2 with many looped structures is able to change the flow direction and flow velocity to meet the water supply needs for the rest of the WDS when some segments are isolated. However, DMA1 consists mainly of branched structures where most pipes only have unique and fixed flow direction (i.e., from water inlet flows to demand nodes). Therefore, after some areas are isolated, the flow in DMA1 is cut off and there is no possibility of changing the flow directions.

Fig. 6 shows the number of valves that need to be closed in order to isolate each failed pipe. By comparing the results from the two DMAs, Fig. 6 shows that the pipes distributed in the looped structures and without nearby valves generally require more valves to

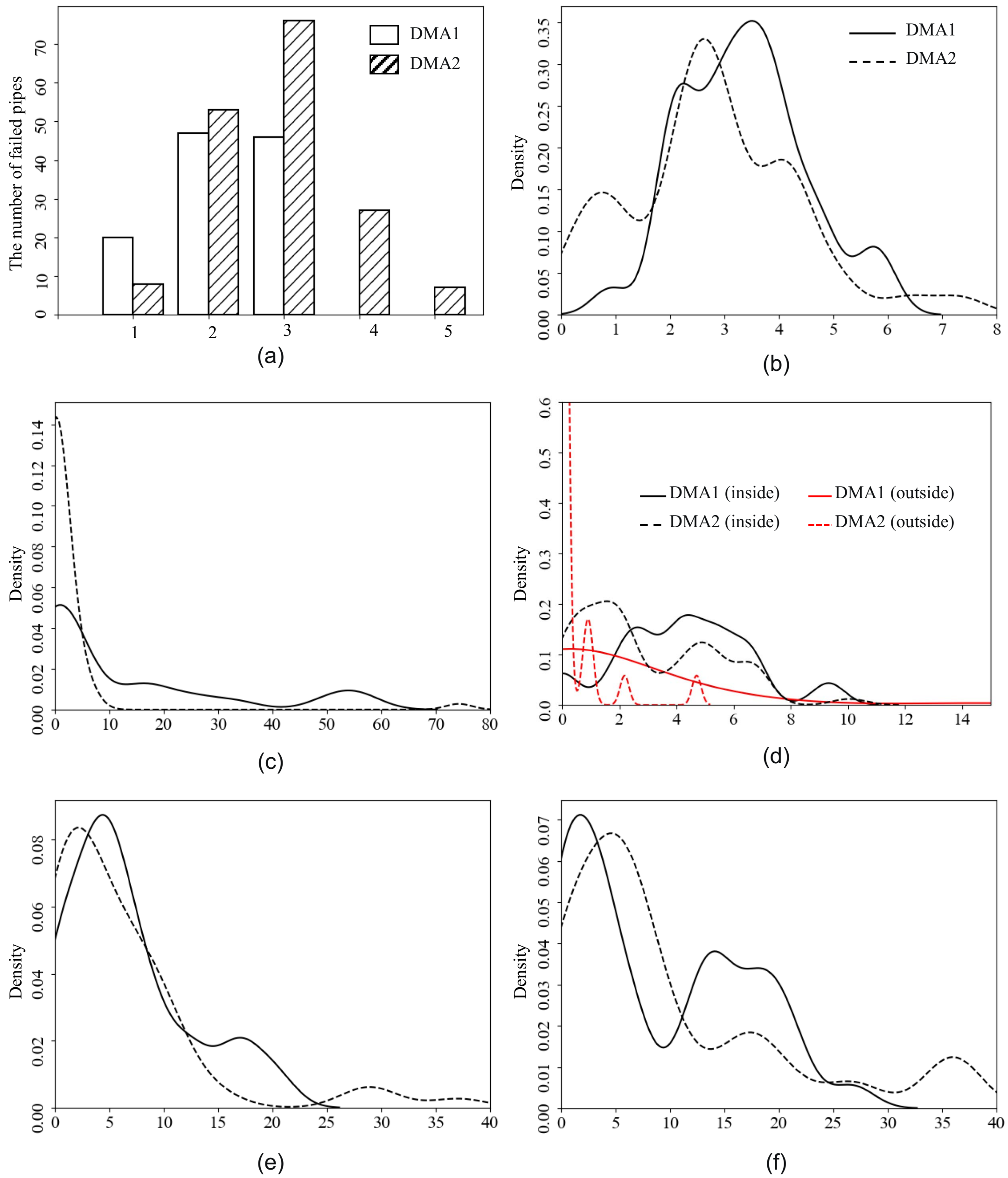

Fig. 5. Statistical distributions of six performance metrics for DMA1 and DMA2: (a) number of closed valves; (b) ratio of the pipe length in the isolated segment (%); (c) ratio of affected pipe length outside the isolated segment (%); (d) ratio of the affected people (%); (e) ratio of pipe length with inversed flow directions (%); and (f) ratio of pipe length with affected flow velocities (%).

form an isolation zone, while pipes distributed at the extremities of the WDS (indicated by black pipes) usually need only one valve to isolate the failed pipe.

Fig. 7 presents the spatial distribution of metric values under two different isolation valve closure (IVC) scenarios in DMA1 and DMA2. Nodes in red indicate that the population associated with the demand node is affected. It can be seen from this figure that the IVCs not only affect the isolated segment but also have adverse effects on other parts of the WDS. This is because the isolation segment blocks a portion of the water supply path, and the pressure and volume of water supplied by the pipes located downstream of the isolation segment will be affected, which is well reproduced by the pressure-driven model used in this study. Comparing different scenarios of the same system, it can be seen that IVCs for pipe failures at different locations result in different impacts on the system. In general, IVCs for pipes located upstream of the system or loops [Figs. 7(a and b)] have more serious consequences than those located at the end of the WDS [Figs. 7(c and d)].

Furthermore, for these two different DMAs, it is found that the hydraulic impacts caused by the IVCs in DMA1 are greater than those of DMA2, while the water quality risk in DMA2 is greater than that of DMA1. The main reason for this phenomenon is again attributed to the different topological structures of the two DMAs. More specifically, for the DMA mainly dominated by branched structures (i.e., DMA1), the IVC is highly likely to cause the interruption of the water supply, which accordingly affects the water supply volume and pressure at the downstream nodes/pipes in the isolated segment. Meanwhile, for the DMA that involves many

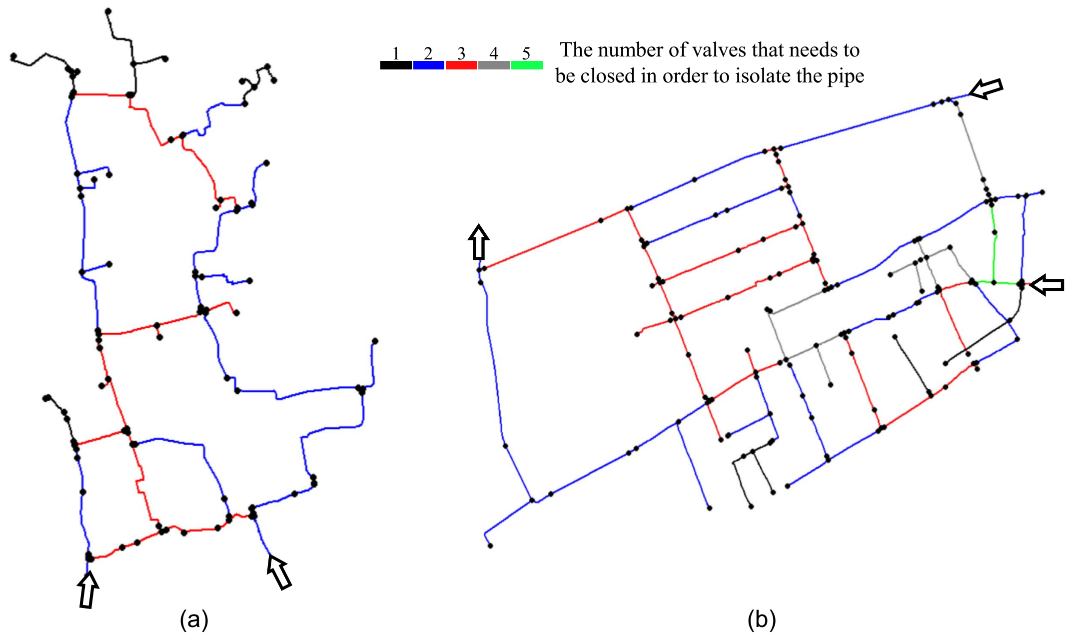

Fig. 6. Number of valves that need to be closed in order to isolate the pipe in (a) DMA1; and (b) DMA2.

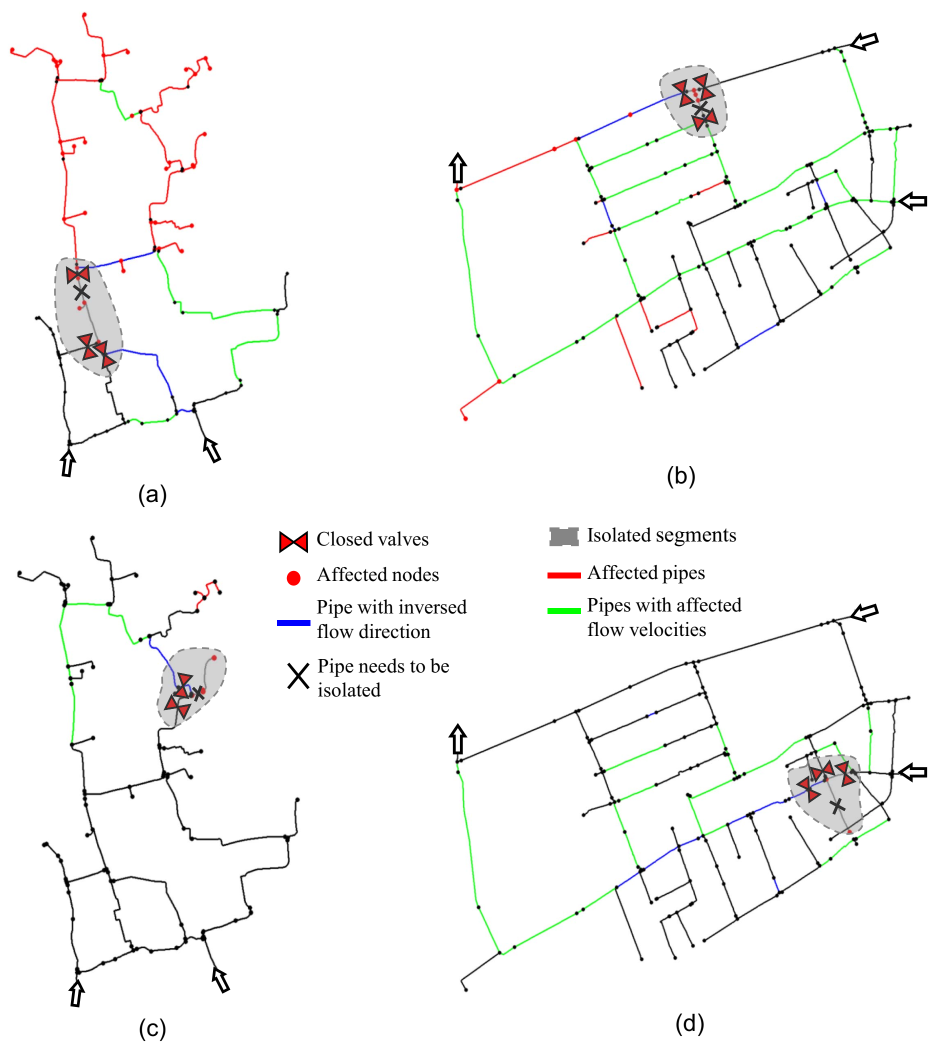

Fig. 7. Spatial distributions of the six metric values for DMA1 and DMA2 under different IVC scenarios: (a) IVC scenario 1 for DMA1; (b) IVC scenario 1 for DMA2; (c) IVC scenario 2 for DMA1; and (d) IVC scenario 2 for DMA2.

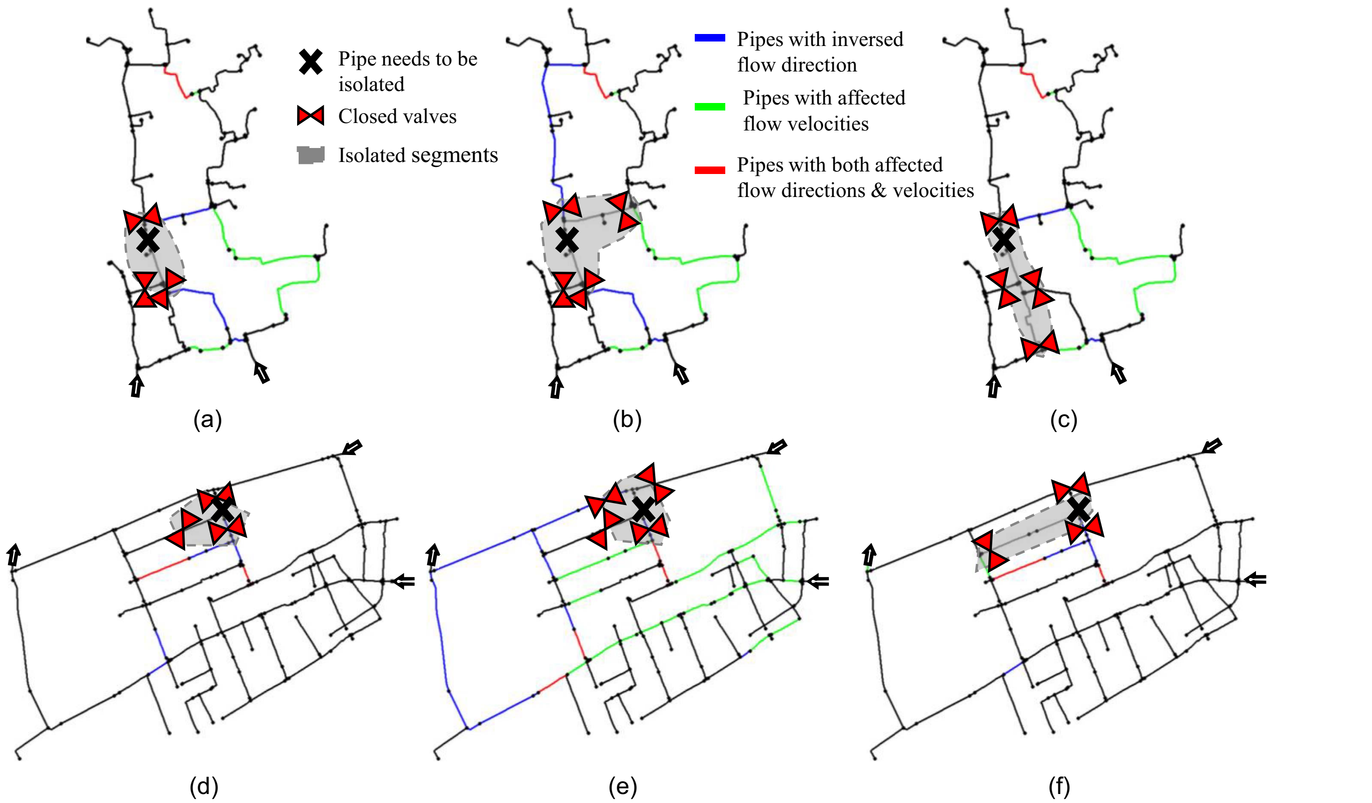

Fig. 8. Distributions of pipes with potential water quality risk induced by IVCs with different strategies for a pipe failure scenario in DMA1 and DMA2: (a) VCS1 for DMA1; (b) VCS2 for DMA1; (c) VCS3 for DMA1; (d) VCS1 for DMA2; (e) VCS2 for DMA2; and (f) VCS3 for DMA2.

Table 2. Metric and ranking values under different valve closure strategies (VCSs) for a certain pipe failure scenario j in DMA1 and DMA2

	DMA1			DMA2		
Metrics	VCS1	VCS2	VCS3	VCS1	VCS2	VCS3
Number of closed valves, Ω_j^c	3	4	4	3	4	3
Length of pipes in the isolated segment (km), IA_j	2.77	6.00	5.76	0.27	0.83	2.13
Length of affected pipes outside the isolated segment (km), AH_j	38.95	35.72	38.95	0.00	0.00	0.00
Number of affected people ($\times 10^3$), AP_j	50.58	50.58	52.96	20.46	21.03	24.06
Length of pipes with inversed flow directions (km), AD_j	8.70	13.40	5.46	4.43	15.40	3.86
Length of pipes with affected flow velocities (km), AV_j	13.85	13.85	13.85	1.52	15.56	2.19
Average ranks, R	1.33	1.83	1.83	1.17	2.33	1.83

looped structures (i.e., DMA2), the water supply continues for most of the water demand nodes after IVCs, but this is at the expense of many pipes with changes in flow directions and sudden increases in flow velocities.

It should be highlighted that a distribution map like Fig. 7 can be practically very useful as it can greatly facilitate valve closure management. For instance, some actions can be taken for the pipes subject to large secondary impacts from the IVCs, or warnings can be sent to the people living in the area with large hydraulic or water quality impacts.

Impacts of IVCs on WDS Performance under Different Valve Closure Strategies

In this section, the impact of different valve closure strategies (VCSs) on WDS performance is explored. To attain this goal, for a particular pipe failure scenario in DMA1 and DMA2, three different VCSs are considered. These are the VCSs that close the valves closest to the failed pipe (VCS1), shut off the valves on the adjacent loops (VCS2), and close the remote valves on the same loop (VCS3). It should be highlighted that these three VCSs are only used to illustrate the utility of the proposed metrics in the present study, and any other VCSs can be straightforwardly accounted for to enable impact analysis. The resultant metric values can be used to assist the decision-making process regarding the selection of the optimal VCS. Fig. 8 shows three different VCSs considered for DMA1 and DMA2, as well as the distribution of pipes with potential water quality risk. Table 2 tabulates all the metric values and rank values for different VCSs.

As shown in Fig. 8, for the same pipe failure scenario, different VCSs can produce different consequences in terms of water quality impacts. Interestingly, valve closures not only affect the water supply in the isolated segment, but also increase the water quality risk of pipes outside the isolated segment even for those with a relatively long distance to the isolated segment. This highlights the great importance of a comprehensive analysis of the potential secondary impacts caused by IVCs with the aid of the proposed metrics and framework. To be specific, for the certain pipe failure scenario in both DMA1 and DMA2 as shown in Fig. 8, VCS1 (i.e., closing the valves closest to the failed pipe) has a relatively low impact on WDS performance because it has the lowest rank value, 1.33 and 1.17, respectively, as can be seen from Table 2. In contrast, VCS2 (i.e., closing the valve on the adjacent loops) has the greatest impact, with rank values of 1.83 and 2.33.

It can be seen from Table 2 that VCS2 mainly affects water quality impact metrics, including flow directions and velocities of pipes. For instance, VCS2 causes an increase of pipes with changed flow directions in DMA1 to 4.7 km. For DMA2, VCS2 causes an increase to 10.97 km of pipes with changed flow directions and 14.04 km of pipes with a sudden increase in flow velocities. This is because closing the valves on adjacent loops may cause some looped structures to be broken, and a part of the pipes in the remaining looped structures of the WDS have to change the flow directions and flow velocities to meet the water supply needs [see Figs. 8(d and e)], which accordingly lead to greater water quality risk. There are more looped structures in DMA2 than in DMA1, so most of the water supply paths in DMA2 can still be connected while many of those in DMA1 are truncated when the isolation segment is formed. As a result, DMA2 has more pipes that can undergo changes in flow directions and flow velocities, so that the changes in the metrics of AD_j and AV_j become more significant than in DMA1.

Impacts of IVCs on WDS Performance under Different Valve Placement Strategies

The proposed framework of six metrics can also be used to develop optimal valve placement strategies (VPSs). As presented in Fig. 9, two new strategies of valve addition are adopted for DMA1 and DMA2, respectively. These are adding valves near nodes with large water demands (VPS1) and adding valves on important looped structures (VPS2). The two strategies add three and four valves to DMA1 and DMA2, respectively, and the way to add valves is shown in Fig. 9. For these VPSs, the isolation segment is formed by closing the valves closest to the failed pipe, with the metric and ranking values presented in Table 3.

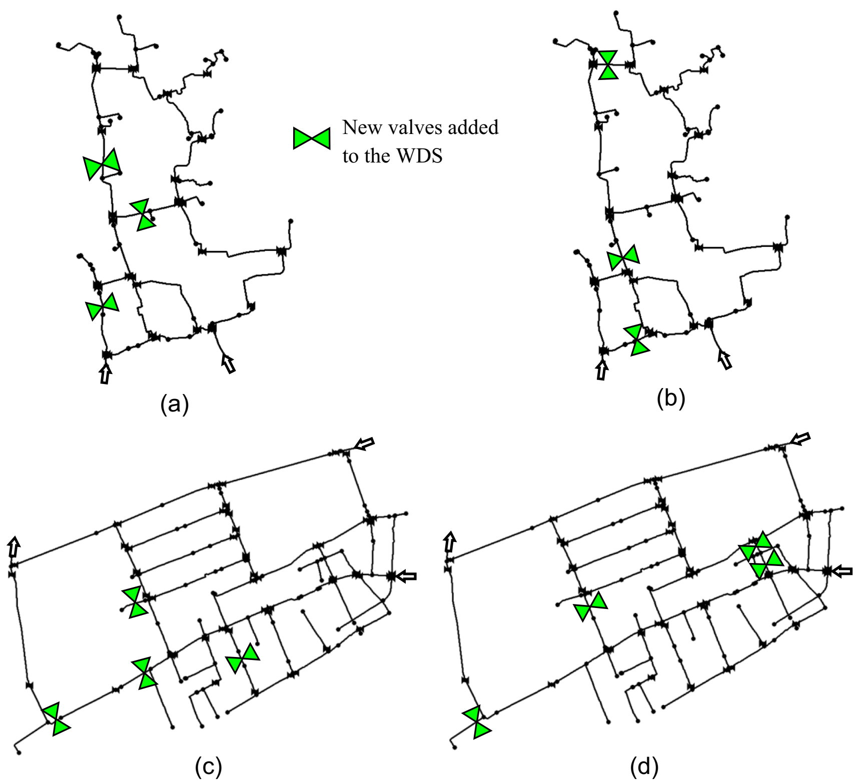

Fig. 9. Different valve placement strategies (VPSs) for DMA1 and DMA2: (a) VPS1 for DMA1; (b) VPS2 for DMA1; (c) VPS1 for DMA2; and (d) VPS2 for DMA2.

Table 3. Metric and ranking values under different valve placement strategies (VPSs) in DMA1 and DMA2

	DMA1			DMA2		
Metrics	Original	VPS1	VPS2	Original	VPS1	VPS2
Number of closed valves, Ω^c	2.23	2.21	2.16	2.84	2.86	2.76
Length of pipes in the isolated segment (km), IA	2.39	2.19	2.24	1.66	1.54	1.50
Length of affected pipes outside the isolated segment (km), AH	8.94	9.39	9.79	1.15	1.18	1.18
Number of affected people ($\times 10^3$), AP	8.79	7.89	8.62	6.49	6.24	5.86
Length of pipes with inversed flow directions (km), AD	4.70	4.69	4.76	3.47	3.53	3.40
Length of pipes with affected flow velocities (km), AV	6.21	6.31	6.30	5.78	6.12	5.81
Average ranks, R	2.00	1.83	2.17	2.00	2.50	1.33

Table 3 indicates that adding new valves at different locations can result in different impacts induced by IVCs. Interestingly, it is found that adding new valves does not guarantee to improve the performance of the original valve system. For example, the comprehensive performance metric (R) values of VPS2 in DMA1 and VPS1 in DMA2 are lower than those of the original ones. While the size of the isolation segment (IA) can be reduced for these two VPSs, the hydraulic and water quality impacts have increased as shown in Table 3. This implies that for some situations, reducing the size of the isolation segment may cause more nodes and pipes outside the isolation segment to be affected. Therefore, it is unreasonable to arbitrarily add valves or minimize the isolation segment, and this further highlights the importance of the proposed metrics that can comprehensively measure the secondary impacts of various VPSs.

Table 3 also implies that in DMA1, VPS1 has the most obvious advantage of reducing the overall impact of IVCs, while VPS2 is the best one in DMA2, with rank values of 1.83 and 1.33, respectively. This shows that there is no specific optimal way to add valves in two WDSs with different structures. Taking the two WDSs compared in this study as an example, in the WDS composed mainly of branched structures, the improvement is obvious when valves are added around nodes with large water demands; in the WDS consisting mainly of looped structures, the improvement is great when valves are added to important loops. These findings can be used to guide valve placements in engineering practice.

Application of the Proposed Method to a Real-World Case Study JXN

This section aims to demonstrate the applicability of the proposed metrics and framework in handling the WDS with a complex structure and large scale. Taking a large network JXN [Fig. 3(c)] as an

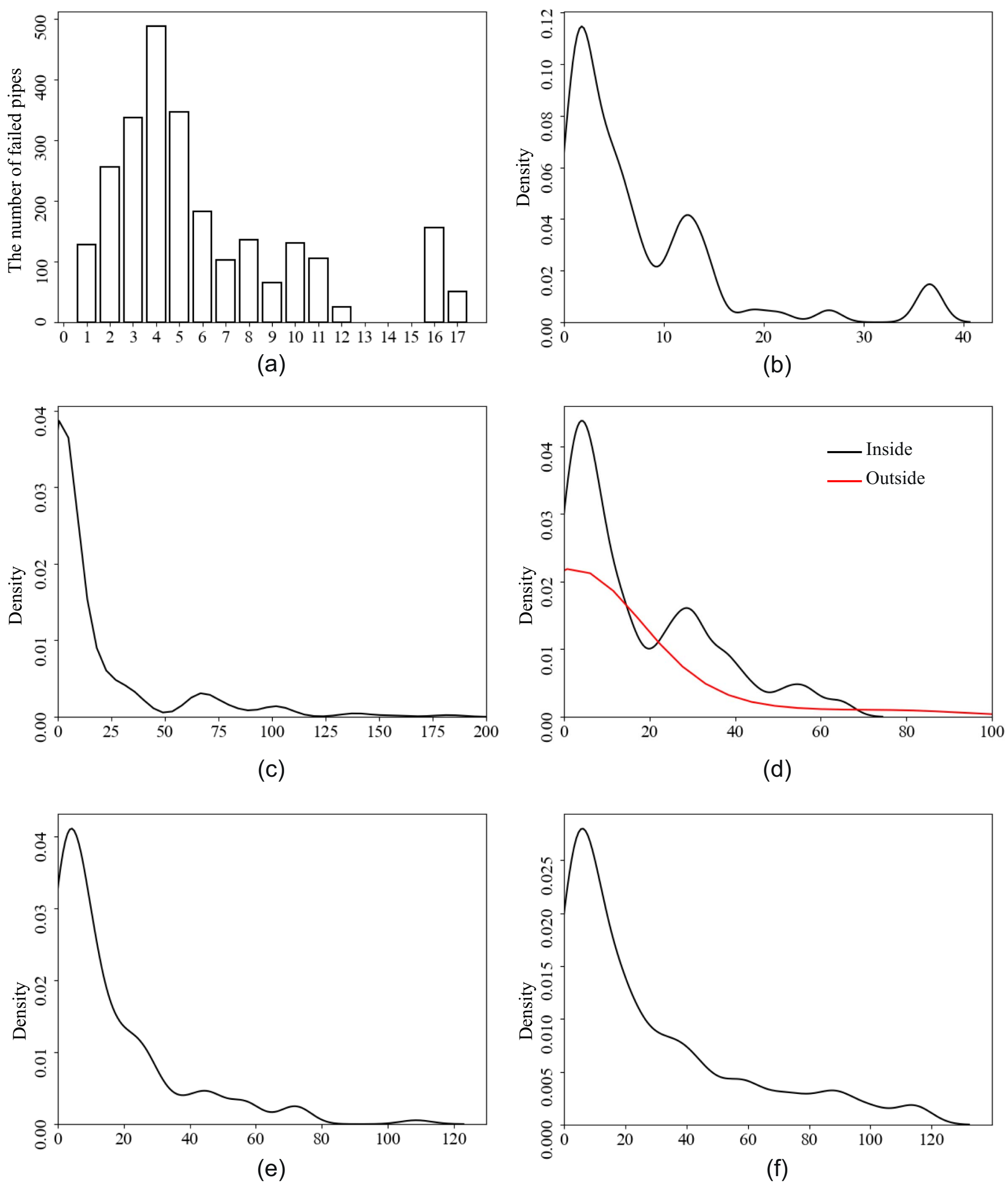

Fig. 10. Statistical distribution of six performance metrics for JXN: (a) number of closed valves; (b) length of pipes in the isolated segment (km); (c) length of affected pipes outside the isolated segment (km); (d) number of affected people ($\times 10^3$); (e) length of pipes with inversed flow directions (km); and (f) length of pipes with affected flow velocities (km).

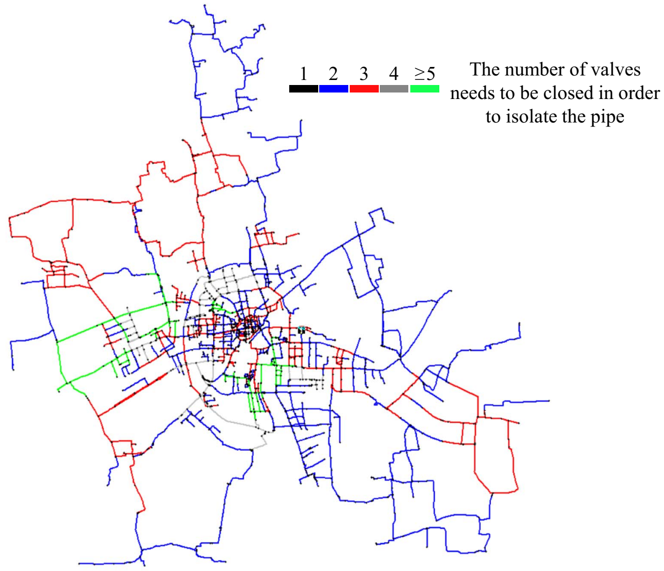

Fig. 11. Number of valves that need to be closed to isolate the pipe in JXN.

example, the results of the applied methodology are shown in Fig. 10. It can be seen from Fig. 10(a) that the majority of pipes in the entire system can be isolated by closing less than five valves, but some pipes need to close a large number of valves (up to 17). This information can be used to guide the decision-making process regarding whether there is a need to add more valves to the existing system. Fig. 11 shows the distribution of the number of valves that need to be closed for pipe isolation. As shown in this figure, for the pipes in the looped structures it is often needed to close a larger number of valves to complete the isolation, while the branch pipes and pipes at the outskirts of the WDS need to operate fewer valves. Therefore, it can be prudent to increase the number of valves in the looped parts to improve the isolation efficiency for the JXN.

As shown in Fig. 10(b), for the majority of the pipe failure scenarios, the length of pipes in the isolated segment is between 5 and 12 km, which is relatively small compared with the total length of the WDS (838.55 km). This indicates that for the entire system, the valve placement is reasonable based on the size of the isolated segment. As for the hydraulic impacts [Figs. 10(c and d)], it is found that statistical distribution trends for the length of affected pipes outside the isolated segment (LA_j) are similar to those of the number of affected people (AP_j) outside the isolation zone. This is due to the fact that the reduction of water supply caused by insufficient pressure also affects the people associated with these demand nodes. In addition, the value of LA_j can be up to 200 km (about 25% of the total length of the WDS), and AP_j can be up to 60,000, showing that the water volume and water pressure of the WDS can be seriously affected after some areas are isolated. Concerning water quality impacts, both metrics of AF_j and AV_j caused by many IVC scenarios are about 10 km. However, there are still some extreme cases where both metrics can exceed 100 km, which can pose a serious water quality threat (LeChevallier 1990; Kowalski et al. 2010; Abraham et al. 2018). The failed pipes with IVCs that can produce large consequences need to be carefully treated during regular checks and maintenance.

For a pipe failure scenario in JXN, three different valve closure strategies are suggested by the local water utility. These are closing the valves closest to the failed pipe (VCS1), closing the valve on the pipes with multiple downstream branches (VCS2), and VCS3 as shown in Fig. 12. Note that VCS3 is similar to VCS2, but keeps two of the valves located at the end pipes of WDS open. The impacts are assessed using the proposed metrics, with results given in Fig. 12 and Table 4. It can be seen that VCS1 is still the optimal one with a rank value of 1.50, indicating the lowest impact on the performance of the JXN. In addition, comparing VCS2 and VCS3, it is found that the hydraulic and water quality impacts of VCS3 are lower than those of VCS2. This suggests that in this case study keeping the valves on the end pipes of WDS open may reduce the impact of valve isolation on the WDS.

For the full-size JXN case study, there is a plan to place another 10 valves in order to improve the performance of the valve system. Two valve placement strategies (VPSs) are available, that is, adding new valves on the loops farthest away from the water source (VPS1) or adding them near the water source (VPS2) as shown in Fig. 13. It can be seen from Table 5 that compared with the original valve system, both VPSs are able to mitigate the impacts of valve isolation on WDS performance in terms of the metric values. However, comparing VPS1 and VPS2, it can be found that adding the same number of valves to the loops close to the water source (i.e., VPS2) reduces more the impact of valve isolation on WDS performance than VPS1, which makes VPS2 more cost-effective. This is because the pipes close to the source are large-diameter pipes and deliver comparably larger water volumes, and the consequences of their failures or isolations are more pronounced. Therefore, enhancing valve placement density in this area facilitates more efficient blocking of these high-consequence pipe failure events.

Conclusions

The present study attempts to improve the understanding of secondary impacts caused by isolation valve closures (IVCs) on WDS performance with the aid of six proposed metrics and a framework. These metrics focus on identifying physical, hydraulic, and water quality aspects of the impacts induced by each IVC scenario within a WDS, namely, (1) the number of closed valves; (2) the length of pipes in the isolated segment; (3) the length of affected pipes outside the isolated segment; (4) the number of affected people; (5) the length of pipes with inversed flow directions; and (6) the length of pipe with affected flow velocities. In addition, a comprehensive rank metric is proposed to simultaneously account for all six metrics to enable the impact analysis.

A framework is proposed to investigate the statistical behavior and spatial characteristics of the impact of IVCs on WDS performance under different system topologies, valve closure strategies, and valve placement strategies with the aid of the proposed metrics and a pressure-driven model. Three real WDS case studies, including two DMAs and one full-size network, are used to demonstrate the utility of the proposed performance metrics and application framework. Based on the results obtained, the key findings from this study are as follows:

1. The proposed metrics can reveal in an effective manner the underlying impacts caused by IVCs on WDS performance, especially regarding the associated water quality risk even for the pipes that are far away from the isolated segment. These metrics cover the physical, hydraulic, and water quality impacts, representing the most comprehensive analysis regarding the secondary impacts induced by IVCs in the literature so far.
2. In addition to the hydraulic impacts, two new water quality metrics and a comprehensive rank metric are proposed in this study. Application results from these two water quality metrics show that the major impacts outside the isolated segment are the

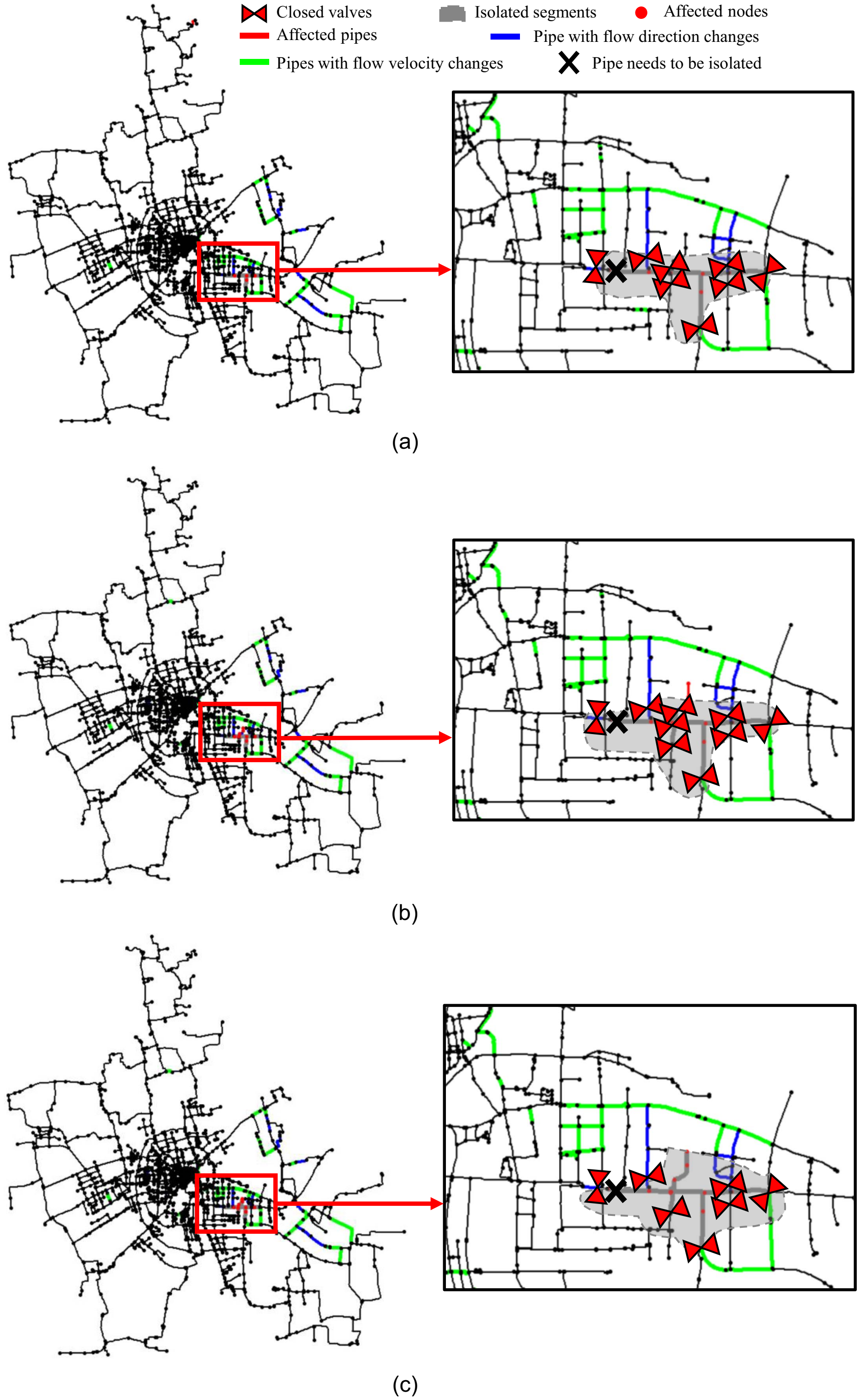

Fig. 12. Impacts on the JXN performance for a pipe failure scenario with different valve closure strategies (VCSs): (a) VCS1; (b) VCS2; and (c) VCS3.

increased water quality risk as many pipes are subject to flow reversal or sudden velocity increases. These findings are useful for guiding the risk management of valve closures in the WDS.

3. It is found that after a failed pipe is isolated, a WDS with branched structures tends to have severe consequences in the hydraulic aspect while a WDS with many looped structures usually has a pronounced impact on water quality. This is because the isolation of branched structures is likely to cut off the water supply path and accordingly affect the water supply in the downstream of the isolated segment. When compared with a branched pipe system, the looped system can continue to supply water for the downstream of the isolated segment, but it is at the expense of changes in flow directions and velocities in the remaining pipes, which, in turn, cause water quality issues.

Table 4. Metric and ranking values under different valve closure strategies (VCSs) for a certain pipe failure scenario j in JXN

Metrics	VCS1	VCS2	VCS3
Number of closed valves, Ω_j^c	8	9	7
Length of pipes in the isolated segment (km), IA_j	4.98	5.83	6.59
Length of affected pipes outside the isolated segment (km), AH_j	0.78	0.77	0.01
Number of affected people ($\times 10^3$), AP_j	14.40	26.59	26.59
Length of pipes with inversed flow direction (km), AD_j	18.81	20.00	19.41
Length of pipes with affected flow velocities (km), AV_j	34.42	36.35	35.79
Average ranks, R	1.50	2.50	1.83

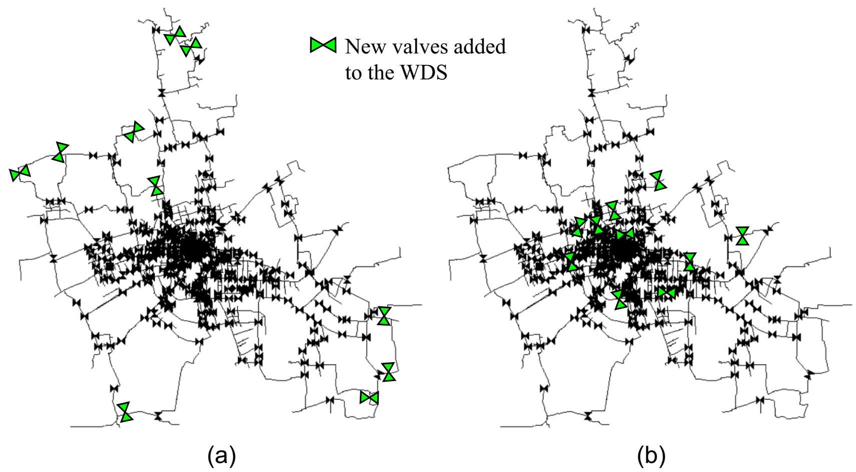

Fig. 13. Different valve placement strategies (VPSs) for the JXN: (a) VPS1; and (b) VPS2.

Table 5. Metric and ranking values under different valve placement strategies (VPSs) in JXN

Metrics	Original	VPS1	VPS2
Number of closed valves, Ω^c	5.95	5.94	5.88
Length of pipes in the isolated segment (km), IA	7.48	6.94	7.19
Length of affected pipes outside the isolated segment (km), AH	20.34	19.89	19.40
Number of affected people ($\times 10^3$), AP	31.25	29.74	29.90
Length of pipes with inversed flow directions (km), AD	15.89	16.02	15.82
Length of pipes with affected flow velocities (km), AV	28.20	28.52	28.12
Average ranks, R	2.67	2.00	1.33

4. Different valve closure strategies can form different isolation zones, which produce different impacts on WDS. Closing the valve on the adjacent loops has the greatest impact on WDS because it will cause more pipes to change flow directions and increase the flow velocities to meet water demand at some nodes. Furthermore, different valve placement strategies can also have different effects on the original valve system, which may improve or deteriorate its performance. Adding valves can effectively reduce the size of the valve isolation segments, but, in some cases, this will be at the expense of improving water quality risk. In the two DMAs considered in this paper, the valve system in branched structures achieves a good improvement in overall performance metric by adding valves near the node with large water demands, while in looped structures a good improvement is achieved when valves are added within the loop. In the complex and large real JXN, placing newly added valves on the loops close to the water source has a low impact on WDS after IVCs.

The findings in this study not only improve the understanding of the secondary impacts of valve closures on WDS performance, but also provide a valuable guideline for water engineers and practitioners from water utilities to design, operate, or manage valve systems. Moreover, the newly proposed evaluation framework in this study with six quantitative metrics is demonstrated in the three cases presented in this paper. The methodology is generic as it can be applied to any other real-world system with diverse configurations and operations (e.g., with appropriate selection of different parameters with system scales and operation characteristics). While the approach can be generally applied, the results of the three case studies may not be readily generalized, but they indicate the need to conduct a comprehensive analysis of the secondary IVC effects on WDS performance and detail the procedure of how to do it. It is acknowledged that limitations of this study may exist, including (1) the EPANET model used in this study allocates demand to the nodes at either end of the pipes, which may lead to small inaccuracies in estimating demand shortfalls; (2) the cost variation of

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valve placement and operation with system scales is not considered in this study; and (3) the segment in the cases used in this study is larger than most of those in developed countries, and hence more real, complex WDSs are needed to demonstrate the utility of the proposed method. Future studies need to be undertaken to address the above limitations.

Data Availability Statement

All data, models (INP files), or codes that support the findings of this study are available from the corresponding author upon reasonable request. The models (INP files) used in this study are available as Supplemental Materials, where these data are executed using the free software downloaded from https://www.epa.gov/water-research/epanet.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (52179080), and the NSFC/RGC Joint Research Scheme (Grant Nos. 52261160379 and N_PolyU599/22). Furthermore, Prof. Savic has received funding from the European Research Council (ERC) for the Water-Futures project under the European Union's Horizon 2020 research and innovation program (Grant Agreement No. 951424).

Supplemental Materials

Case study data is available online in the ASCE Library (www.ascelibrary.org).

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