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Review

Analysis, design, and maintenance of isolation valves in water distribution networks: State of the art review, insights from field experiences and future directions

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ABSTRACT

Isolation valves play a primary role in water distribution networks as their operation enables isolating the part of the network undergoing planned or extraordinary maintenance, in the context of rehabilitation or pipe break repairs, respectively. This paper presents a review of the current state of the art of isolation valves, with a focus on the problems of analysis, e.g., assessment of the performance of the network in segment isolation scenarios, design of optimal valve locations, and selection criteria/methods for identification of the valves to maintain. After describing and classifying the main scientific contributions, the paper proceeds by reporting the results of a survey to water utility staff in the United States, Italy, Portugal, and Iran, aimed at analysing the current practices adopted for the positioning and maintenance of isolation valves in real case studies. The paper ends with a discussion on the analysis of scientific literature and results of on-field surveys, highlighting critical points for potential future developments, including the connection between the design and maintenance of isolation valves, the trade-off between increasing validity and reducing complexity of reliability assessment methods, and more precise modeling of isolation valves systems.

1. Introduction

Water Distribution Networks (WDNs), critical infrastructures providing safe and adequate drinking water to consumers, are facing increasingly frequent failures due to aging infrastructure, and external stressors, such as climate change and financial constraints (Trietsch and Vreeburg, 2005; Diao et al., 2016).

Based on the World Water Development Report in 2018 (WWDR, 2018), about half of the global population, or 3.6 billion people, live under water scarcity, with this number being estimated to rise to 57% by 2050. Alarmingly, more than 30% of withdrawn water (with peaks of roughly 60% in aged and/or poorly maintained systems) is lost within WDNs, primarily due to component failure (Duan et al., 2020). In the United States alone, it is estimated that about 240,000 water main breaks occur annually, causing the daily loss of over 2 million gallons of drinking water (ASCE, 2017). In developing countries, water losses from WDNs could potentially rise to 60% (Macharia et al., 2020).

These statistics underscore the urgent need for improved WDN management and maintenance strategies, aimed at reducing water loss, mitigating failure impact, and ensuring proper allocation of water resources. Historically, most research and intervention efforts have predominantly focused on the rehabilitation, repair, or replacement of pipes — considered the primary source of network failure.

Although this approach is vital, it does not entirely resolve the issue. Other network components, specifically isolation valves, are crucial in managing network performance under various failure conditions. Over the past few decades, both academia and industry have observed a significant shift towards investigating the role of isolation valve system (IVS) in mitigating network failures. This is partly driven by the understanding that operational strategies or structural changes alone cannot eliminate the need for repairs, even in renovated infrastructures. Indeed, problems occur in all systems, and isolation valves are the key to

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preventing a single pipe break from having a significant impact on the system. Additionally, the cost of pipe repairs and replacements can be prohibitive, especially for utilities working within budget constraints while trying to maintain satisfactory service levels.

Isolation valves, known for their basic 'open or close' functionality, are essential for segmenting WDNs during maintenance and emergency situations. As shown in Fig. 1 for a conceptual WDN, these valves subdivide the network into smaller parts, often referred to as “segment”.

These valves effectively restrict water flow in certain sections, thus minimizing service disruption and assisting in the reduction of non-revenue water, which represents one of the key targets under the United Nations' Sustainable Development Goals (United Nations, 2015).

However, the placement of isolation valves constitutes a complex task, requiring a careful balance between cost-effectiveness, operational reliability, maintenance, and resilience under varying hydraulic conditions. Additionally, isolation valves themselves are prone to failure and need effective maintenance strategies to remain operational. For instance, there are estimations that up to 40% of valves in the WDNs of the United States may be inoperable (Baird, 2011). On top of all that, there is a lack of universally accepted methods for evaluating the performance of IVSs under different operating conditions. Consequently, decision-makers in the water industry often struggle to select the most suitable management strategy for isolation valves and their optimal implementation within WDNs.

The complexity of failure mitigation strategies in WDNs called for research focusing on the design, modeling, evaluation, and maintenance of IVSs. Over the past thirty years, considerable efforts have been dedicated to addressing existing issues and shortcomings within this domain. Numerous researchers have probed several aspects concerning IVSs in WDNs, proposing a range of designs/modeling techniques, and performance evaluation methodologies. However, to the best of our knowledge, there is no review on the subject to provide insights into the current status of IVSs in WDNs addressing any above-mentioned aspects. Therefore, this study aims to provide a comprehensive review of the state-of-the-art developments regarding IVSs in WDNs from different perspectives, including technical, modeling, and practical viewpoints, while critically assessing and comparing the available solutions. Furthermore, common challenges and future directions associated with various aspects of IVSs are identified. The specific goals of this review are:

- To provide a thorough summary and detailed discussion on the present state of IVSs in WDNs, covering control, modeling, design, optimal positioning, use strategy studies;
- To critically examine potential challenges and issues associated with the application/operation/management of IVSs within WDNs; and
- To extrapolate future trajectories and identify research needs and potential directions.

The remainder of the paper is organized as follows. Section 2 presents the review methodology employed in this study. In Section 3, an in-depth and critical review of the IVSs in WDNs is provided. Section 4 analyses the current engineering practice by reporting the experience collected by surveys of water utility staff worldwide. Section 5 presents the discussion on current issues and future perspectives derived from this study, followed by conclusions in Section 6.

2. Review methodology

Sixty-six manuscripts, published over the past three decades, from the beginning of 1993 to the end of 2022, were considered in this review concerning isolation valves in WDNs. It is expected that the chosen review timeframe is sufficient for encapsulating comprehensive advancements of studies on IVSs in WDNs. The reviewed papers are identified using the keywords “*Isolation valve*”, “*mechanical/system reliability*”, “*segments*” in “*water distribution network/system*”, and “*water supply network/system*” in the Scopus database.

As is shown in Fig. 2, over the last thirty years there has been an increasing interest in studying the IVS in WDNs. Notably, following the publication of two papers in the initial interval (1993-1997), a gap

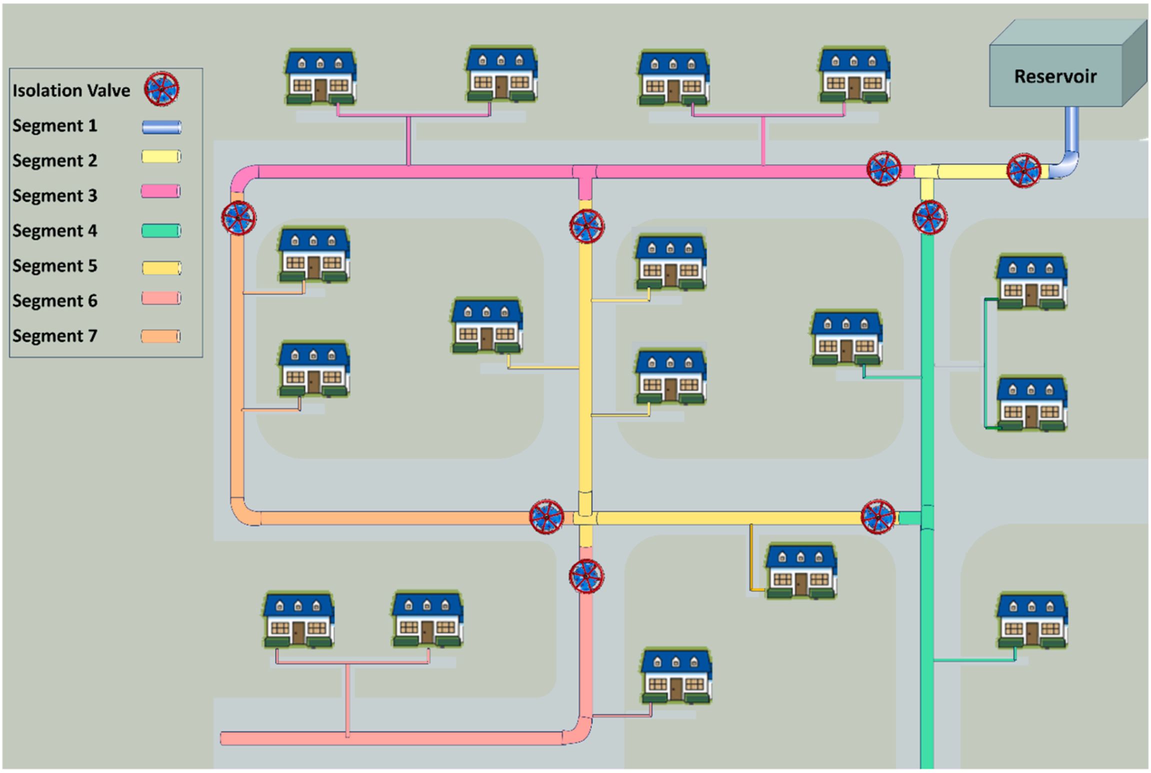
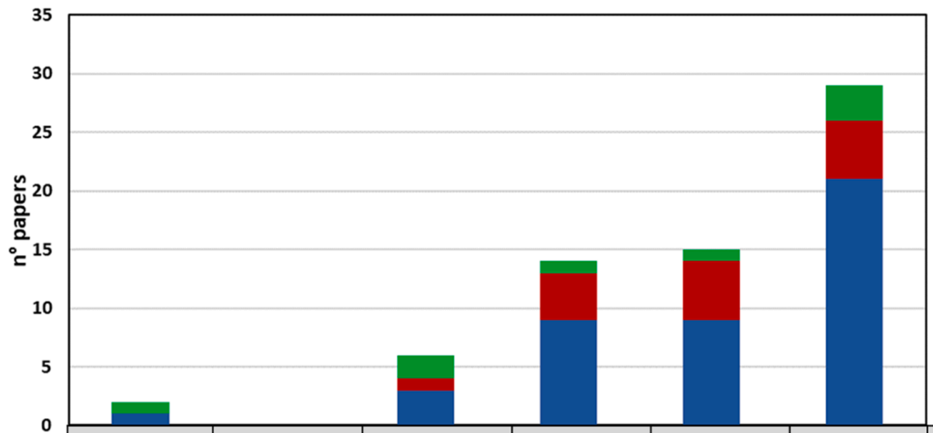


Fig. 1. Conceptual WDN with an IVS subdividing it into color-coded segments.



	1993-1997	1998-2002	2003-2007	2008-2012	2013-2017	2018-2022	Total
🟦 **Analysis**	1	-	3	9	9	21	43
🟥 **Design**	0	-	1	4	5	5	15
🟩 **Maintenance**	1	-	2	1	1	3	8

Fig. 2. Temporal distribution – in 5-year intervals – of the three macro-categories in which the 66 selected paper are divided in this review.

emerged with no published research on IVSs during the next 5-year period (1998-2002). However, there has been a rapid rise in published contributions on this topic in the subsequent 5-year intervals, highlighting the increasing attention on the subject.

Upon analysing the selected papers, three distinct macro-categories were defined (color-coded in Fig. 2) based on the primary objective of the study conducted. The temporal distribution corresponding to these categories is shown in Fig. 2. The "*Analysis*" category, holding the majority share of the selected papers (43 out of 66), includes all papers dealing with various aspects of modeling and evaluating IVSs and WDN performance. Notably, there is a significant increase in attention towards research on methodologies for the optimal design of IVSs ("*Design*" category), with 15 out of the 66 papers focused on this. The "*Maintenance*" category, which is the least explored (8 out of 66 papers), refers to studies concerning the impact of isolation valve failures on WDN performance, and maintenance strategies to minimize the effects and frequency of such failures. This review is structured based on this primary classification, with the discussion of papers organized accordingly.

3. State of the art of isolation valve systems in WDNs IVSs

In the following subsections, a comprehensive and critical review of studies on IVSs in WDNs is provided within the categories mentioned above, namely *Analysis* (Section 3.1), *Design* (Section 3.2), and *Maintenance* (Section 3.3).

3.1. Analysis

3.1.1. IVS modeling

Spurred by Walski (1993a)'s idea to utilize segment/valve topology as opposed to the conventional pipe/junction topology in analysing IVS in WDNs, most studies have embraced this approach. In this dual topology, the valves are the edges, and the segments, which are the smallest portions of the network that can be isolated by closing the valves, are represented as single nodes.

Several studies (listed in Table 1) were directed towards the identification of segments (Jun and Loganathan, 2007; Giustolisi et al., 2008a; Li and Kao, 2008; Saldarriaga et al., 2009; Creaco et al., 2010a; Gao, 2014; Jeong et al., 2021; Hernandez and Ormsbee, 2021a), valve and segment topology characterization (Jun et al., 2004; Xiao et al., 2014; Zischg et al., 2019; Huzsvár et al., 2019; Jeong et al., 2021), and pinpointing critical segments (Li et al., 2008; Atashi et al. 2020; Abdel--Mottaleb and Walski, 2021; Giustolisi et al., 2022; Simone et al., 2022; Tornyeviadzi et al., 2022).

Notably, methods for automatic identification and characterization of segments were developed employing the depth-first search algorithm (Bentley Systems, 2005). Jun and Loganathan (2007) also used the depth-first search algorithm for segment identifications. They further introduced an algorithm to detect unintended isolations (i.e., the parts of the network out of the isolated segment that gets disconnected from sources) using the breadth-first search technique, a method later refined by Jeong et al. (2021) and Hernandez and Ormsbee (2021a) through the implementation of link-link and segment-segment adjacency matrices instead of the node-node adjacency matrix, respectively.

Following this, Li and Kao (2008) applied a depth-first search algorithm for segment identification and proposed an articulation point identification method for detecting unintended isolations. Moreover, Li and Kao (2008) and Saldarriaga et al. (2009) developed GIS-based systems for IVS analysis. Gao (2014) enhanced the process of segment identification for large networks by modifying the Warshall algorithm to calculate node transitive closure sets (segments), which enabled simultaneous identification of all the segments.

Alternatively, Giustolisi et al. (2008a) and Creaco et al. (2010a) developed methods based on simplified hydraulic system equations to identify isolated elements. Specifically, Creaco et al. (2010a) identified elements belonging to a specific segment by detecting nodes connected to a fictitious reservoir within the segment. Several other studies also utilized hydraulic simulation tools for segment analysis (Li and Kao, 2008; Saldarriaga et al., 2009; Atashi et al., 2020; Abdel-Mottaleb and Walski, 2021; Tornyeviadzi et al., 2022)

Furthermore, several studies examined different properties of IVSs, subdividing the WDN into smaller segments. Metrics used by Jun et al. (2004) and Xiao et al. (2014) include segment length, number of pipes and nodes within each segment, valve-to-pipe and valve-to-segment ratios, and number of pipes per segment, among other factors. Zischg

Table 1
Studies focused on the IVS modeling from reviewed papers.

Hydraulic simulation	Objective	Method	Reference
-	Segment/valve topology	Dual Segment/Valve topology graph	Walski, 1993a
-	IVS evaluation	Average length of segment, number of valves per pipe, number of valves per segments, impact of failure of valve, reliability of isolating a segment, number of pipes in a segment	Jun et al. 2004
-	Segment identification	Depth-first search algorithm, Breadth-first search algorithm	Jun and Loganathan 2007
(WDN governing equation)	Segment Identification	Simplified WDN governing equation	Giustolisi et al. 2008a
(Freeware)	Segment Identification	Depth-first search algorithm, articulation point identification	Li and Kao 2008
(Software with charge)	GIS system for IVS	Integration of GIS with hydraulic model	Saldarriaga et al. 2009
(WDN governing equation)	Segment Identification	Simplified WDN governing equation	Creaco et al. 2010a
-	IVS evaluation	Number of Affected Elements and Isolation Nodes, Segment Length, Fluid Volume of Segment, Outage Set Length	Xiao et al. 2014
-	Segment Identification	Warshall algorithm, transitive closure of graphs	Gao 2014
-	IVS evaluation	complex network metrics	Zischg et al. 2019
-	IVS evaluation	Node-degree distribution	Huzsvár et al. 2019
(Freeware)	Critical segments	Global resilience analysis (GRA)	Atashi et al. 2020
-	Unintended isolation identification	Breadth-first search algorithm	Jeong et al. 2021
-	Segment Identification	Depth-first search algorithm, Breadth-first search algorithm	Hernandez and Ormsbee 2021a
(Software with charge)	Critical segments	Reachability matrix	Abdel-Mottaleb and Walski 2021
-	Critical segments	IVS Bipartite Graph, Betweenness Centrality	Giustolisi et al. 2022
-	Critical segments	Betweenness Centrality	Simone et al. 2022
(Freeware)	Dynamic segment criticality	Multi-slice network	Tornyeviadzi et al. 2022

et al. (2019) and Huzsvár et al. (2019) proposed metrics based on the graph theory, such as node-degree distribution, modularity, and assortativity of the segment/valve graph.

More recently, Atashi et al. (2020) implemented a global resilience analysis method incorporating the segment/valve topology of WDN to find the most critical segments. Moreover, complex network techniques were used for the identification of critical segments. Abdel-Mottaleb and Walski (2021) developed a reachability matrix to assess the importance and vulnerability of segments, while Giustolisi et al. (2022) and Simone et al. (2022) proposed a method for identifying critical segments and valves using a WDN-tailored Betweenness Centrality. In addition, Tornyeviadzi et al. (2022) employed a multi-slice network approach to capture the dynamic changes in segment importance throughout the day due to fluctuations in demand.

3.1.2. *WDN reliability*

One of the critical facets of analysing the distribution of isolation valves pertains to assessing the reliability of WDNs, which is defined as the ability of a system to maintain adequate service to users even under abnormal conditions (Hashimoto et al. 1982; Wagner et al. 1988a,b). Numerous studies (see Table 2) primarily focused on gauging this reliability by examining the isolation valve distribution. A common metric for reliability used in these investigations is the measurement of unmet user demands, or "demand shortfall", which occurs when a segment containing a failed pipe is isolated. This demand shortfall resulting from mechanical failures is usually subdivided into two main causes, namely topological and hydraulic (Walski et al. 2006, Creaco et al. 2012, Giustolisi 2020, Hernandez and Ormsbee 2017, Hernandez and Ormsbee 2021b). The topological cause refers to unmet demands on pipes that are directly (or indirectly and unintendedly) disconnected from the source due to isolation, while the hydraulic cause is related to unsatisfied demands caused by the pressure drop (due to path redundancy reduction resulting from segment isolation) in the areas of the network that remain connected. Fig. 3 shows the different types of segment isolations and demand shortfalls for a conceptual WDN.

Consequently, the estimation of the hydraulic component of demand shortfall requires performance of a pressure-driven analysis simulation for each segment, which can be either based on extended periods (Bentley Systems, 2005; Giustolisi et al., 2008b; Gupta et al., 2014a; Shuang et al., 2017; Giustolisi, 2020; Berardi et al., 2022; Liu and Kang, 2022) or snapshot simulations (Creaco et al., 2011; Creaco et al., 2012; Berardi et al., 2014; Laucelli and Giustolisi, 2015; Wéber et al., 2020; Hernandez and Ormsbee, 2021b; Hwang and Lansey, 2021; Wéber et al., 2022). Adopting extended-period hydraulic simulation is particularly advantageous and informative in the presence of WDN tanks since this simulation gives insight into the emptying processes that may occur during prolonged outages (Berardi et al., 2022) .

The proposed reliability measures consider either individual failure events or simultaneous multiple incidents. Many studies incorporated the probability of pipe failure when determining reliability. Due to the lack of actual failure rate data, Giustolisi et al. (2008b), Creaco et al. (2012), and Wéber et al. (2020) utilized the lengths of pipes to estimate their respective relative failure likelihoods. Hwang and Lansey (2021) applied a uniform failure rate given the small range of diameters of the pipes assessed in their case study, while Wéber et al. (2022) working on 27 real-world WDNs, calculated failure rates based on historical data, considering the pipes' material, age and lengths. Accounting for the probability of pipe failure prevents overestimating the vulnerability of segments featuring high demand shortfall but low failure probability, and segments with low demand shortfall and high failure probability (Wéber et al., 2020).

Furthermore, Berardi et al. (2014) investigated critical events resulting from the simultaneous failure of multiple pipes, such as those associated with the greatest demand shortfall coupled with the fewest simultaneous failures through a multi-objective optimization. In the context of assessing the reliability of WDNs against seismic events, Laucelli and Giustolisi (2015) adopted a multi-objective optimization framework to find critical scenarios, while evaluating pipe failure probability based on the fragility curves provided by the American Lifelines Association (ALA). Jung et al. (2016) generated seismic events repeating the Monte Carlo simulation to obtain a converged average reliability for the network. Choi and Kang (2020) utilized the fragility curves to model seismic failure events, examining the reliability of the WDN under varying scenarios of valves number.

In the papers examined, most case studies are based on real-world WDN pipe layouts. These layouts either reflect the actual distribution of isolation valves (Walski et al., 2006, Creaco et al. 2012, Wéber et al. 2020, Fiorini Morosini et al. 2020, Hernandez and Ormsbee 2021b, Wéber et al. 2022) or other placement strategies, including N valve or

Table 2
Studies focused on the WDN reliability analysis through IVSs from reviewed papers.

Hydraulic simulation	Methods	Performance Indicator	Case Study Valve Layout	Pipe Failure Model	Reference
_	Segment identification	Average system shortfall	Real, N-1 and N valve	Single	Walski et al. 2006
Extended period PDA (WDN governing equation)	Segment identification	Expected demand shortfall	N valve; Hypothetical	Single	Giustolisi et al. 2008b
Snapshot PDA (WDN governing equation)	Segment identification	Maximum demand shortfall; Weighted average demand shortfall	Optimal; Real	Single	Creaco et al. 2011
(WDN governing equation)	Segment identification	Weighted sum of various demand shortfalls and pressure drops	_	Single	Zheng et al. 2011
Snapshot PDA (WDN governing equation)	Segment identification	Weighted average demand shortfall	Optimal; Real	Single	Creaco et al. 2012
Snapshot PDA (Software with charge)	MOGA; Segment identification	Ratio of supplied demand	Hypothetical	Multiple	Berardi et al. 2014
Extended period PDA (Freeware)	Segment analysis	Node Reliability; Volume reliability; System reliability	Hypothetical	Single	Gupta et al. 2014a
Snapshot PDA (Software with charge)	MOGA; Pipe Seismic Fragility Model	Seismic risk (demand shortfall* joint probability)	Hypothetical; Optimal	Multiple	Laucelli and Giustolisi 2015
PDA (Freeware)	Random seismic event simulation;	Ratio of supplied demand	Random	Multiple; Single	Jung et al. 2016
Extended period PDA (Freeware)	Segment identification; pipe attack simulation	Ratio of supplied demand	Random, N valve	Cascading	Shuang et al. 2017
_	performance deficiencies histogram	Loss of physical connectivity; demand shortfall	_	_	Hernandez and Ormsbee 2017
Snapshot PDA (Freeware)	Segment identification; Statistical analysis	Weighted average demand shortfall	27 real	Single	Wéber et al. 2020
PDA (Freeware)	Seismic damage simulation; Segment identification	System serviceability	N valve; One valve on each pipe	Multiple	Choi and Kang 2020
Extended period PDA (Software with charge)	Segment identification	Weighted average demand shortfall	Optimized	Single	Giustolisi 2020
PDA (freeware)	Segment identification	Weighted sum of segments demand shortfall	Real, hypothetical	Single	Fiorini Morosini et al. 2020
Extended period PDA (Software with charge)	Segment identification	Weighted average demand shortfall	Hypothetical	Single	Berardi et al. 2022
Snapshot PDA (Freeware)	Segment identification; Fire flow demand model	Topological metric; Demand shortfall under various demand conditions	Real	Single	Hernandez and Ormsbee 2021b
Snapshot PDA (Freeware)	Segment identification; Monte Carlo simulations	Average demand shortfall; Weighted average demand shortfall	Random, N-1 and N valve	Single	Hwang and Lansey 2021
Snapshot PDA (Freeware)	Failure statistics analysis; Segment identification	Weighted average demand shortfall	Real	Single	Wéber et al. 2022
Extended period PDA (Freeware)	Segment identification; Recovery strategies	Ratio of supplied demand	Optimized	Single	Liu and Kang 2022

N-1 valve rules (Walski et al., 2006, Giustolisi et al. 2008b, Creaco et al. 2012, Choi and Kang 2020, Hwang and Lansey 2021), hypothetical (Giustolisi et al. 2008b, Berardi et al. 2014, Gupta et al. 2014a, Laucelli and Giustolisi 2015, Fiorini Morosini et al. 2020, Berardi et al. 2022), random (Hwang and Lansey 2021), or optimized (Creaco et al. 2012, Laucelli and Giustolisi 2015, Giustolisi 2020, Liu and Kang 2022) distributions. Notably, it is worth highlighting that the two strategies most adopted in the field are the N valve rule (placement of valves at all pipes connected to each demand node) and the N-1 valve rule (installation of N-1 valves around a node with N connected pipes), which are general rules of thumbs for isolation valve placement (Walski et al., 2006), as shown in Fig. 4. Although employing the N valve rule undoubtedly leads to the highest reliability, Creaco et al. (2012) suggested that similar or slightly lower reliability levels can be achieved using a substantially reduced number of optimally located valves. Furthermore, Hwang and Lansey (2021) demonstrated that a decrease in the valve-to-pipe ratio from 2 (as per the N valve rule) to even 0.9 does not substantially affect the reliability of the systems examined in their case studies.

In addition, Wéber et al. (2022) identified a pattern in the vulnerability of 27 real-world IVSs, finding that the behavior of WDNs mirrors that of scale-free networks. Specifically, most segments exhibit minimal vulnerability, whereas a small sample is critical, notably demonstrating a significant demand shortfall.

The reliability assessment metrics analysed in this study can be classified into five types based on the input data required for estimating them, as shown in Fig. 5. The common formulation for the evaluation of each type of metric is presented in supplementary materials. It must be noted that this classification refers to all the 66 papers considered in this review, as most of the papers, even with a primary focus on IVS design or maintenance, also rely on reliability assessment metrics. Metrics using hydraulic models and pressure-driven analysis represent more real values of demand shortfalls. However, they are constrained by the availability of a reliable model and the much higher computational expenses. Moreover, as pipes are often not equally susceptible to failure, accounting for pipe failure probabilities can significantly impact the reliability assessments' accuracy. Additionally, evaluating reliability against seismic events requires further models and input data for simulating seismic damages to WDN pipes.

3.1.3. *Other analyses*

Few studies have performed analyses involving isolation valves for tackling problems that fall out of the main scope of those mentioned in the previous two subsections. Vamvakeridou-Lyroudia et al. (2011) and Mahmoud et al. (2018) investigated altering the status of isolation valves, other than those required for isolating the failure, as real-time measures to reduce the impact of system failures. Filho et al. (2015) proposed a method based on Strategic Options Development and Analysis (SODA) to identify criteria for evaluating segmentation in WDNs, addressing decision-makers' conflicts. Do et al. (2018) developed a three-step method involving sensitivity analysis of sensor measurements, GA optimization, and the Levenberg-Marquardt method for locating inadvertently partially closed valves. Aghapoor Khameneh et al. (2020) developed a framework to assess failures and associated uncertainties within WDNs, by integrating fuzzy set theory and fault tree analysis, highlighting that around 55% of water supply disruption probability was attributed to the failure of isolation valves.

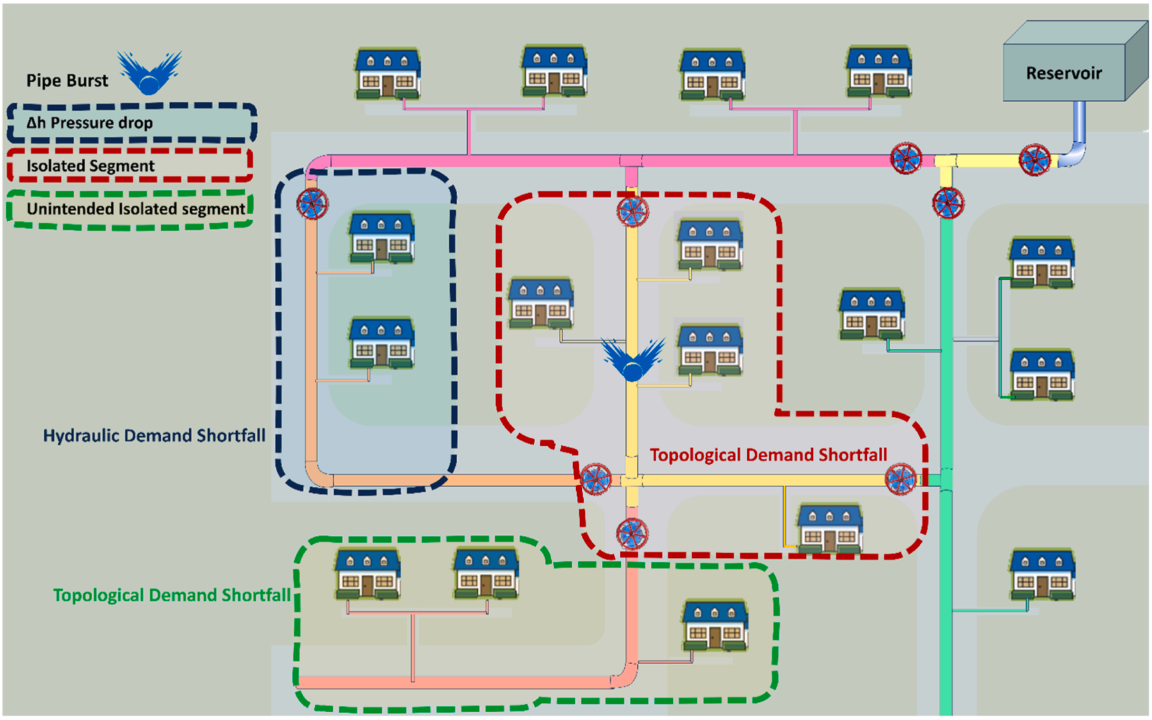


Fig. 3. Topological (intendedly and unintendedly isolated segment) and hydraulic demand shortfalls after the isolation of a segment containing a failing pipe, for a conceptual WDN.

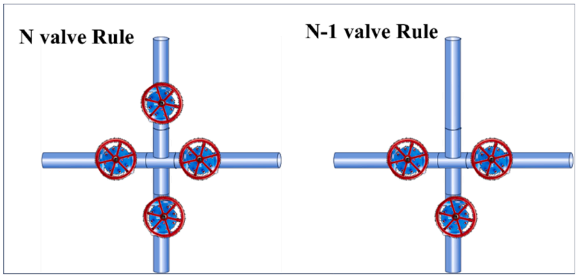


Fig. 4. Example of N valve rule and N-1 valve rule on an intersection.

3.2. Design

The reliability of WDNs has been a crucial factor in their design and rehabilitation strategies. In this literature review, 22% of the studies focus on devising methods to design and rehabilitate WDNs taking into account the role of IVSs (Table 3). Specifically, these methods aim to find the optimal placement of isolation valves (Creaco et al. 2010b; Giustolisi and Savic 2010; Alvisi et al. 2011; Cattafi et al. 2011; Gavanelli et al. 2013; Choi et al. 2018; Kim et al. 2019; Lee and Jung 2021; Yang et al. 2022; Hernandez Hernandez and Ormsbee 2022), or optimal pipe sizing and rehabilitation accounting for IVS layout (Kao and Lee 2007; Giustolisi et al. 2014; Gupta et al. 2014b). All studies adopted the segment/valve topology to evaluate the reliability of WDN and IVS performance. Kao and Lee (2007) demonstrated that using the segment/valve topology led to more effective solutions for rehabilitating pipes than those derived from the conventional pipe/node topology. Furthermore, the majority of studies chose an objective function based on demand shortfalls. Several studies have also accounted for the trade-off between this objective and others such as cost or the number of placed valves (Creaco et al. 2010b; Giustolisi and Savic 2010; Alvisi et al. 2011; Giustolisi et al. 2014; Choi et al. 2018; Kim et al. 2019; Yang et al. 2022). Single or multi-objective genetic algorithms are the most commonly adopted tools for finding design solutions (Creaco et al. 2010b; Giustolisi and Savic 2010; Alvisi et al. 2011; Giustolisi et al. 2014; Lee and Jung 2021; Yang et al. 2022), though some studies used logic programming (Cattafi et al. 2011; Gavanelli et al. 2013) or graph theory techniques (Hernandez Hernandez and Ormsbee, 2022). Notably, the study of Lee and Jung (2021) is the only one that adopted hydraulic simulations with pressure-driven analysis to account for hydraulic demand shortfalls.

As for the placement of isolation valves, studies were either designing a whole new IVS (Creaco et al. 2010b; Giustolisi and Savic 2010; Alvisi et al. 2011; Cattafi et al. 2011; Gavanelli et al. 2013; Lee and Jung 2021) or improving an already existing IVS by adding new valves (Choi et al. 2018; Meng et al. 2019; Kim et al. 2019; Yang et al. 2022; Hernandez Hernandez and Ormsbee 2022). Additionally, Fontana and Morais (2017) developed a multi-criteria approach due to conflicts of decision makers for finding a comprehensive criterion for valve placement. On the other hand, Kao and Lee (2007) and Giustolisi et al. (2014) aimed to find optimal pipe replacement and diameters, respectively, based on the IVS of the WDN. Moreover, Gupta et al. (2014b) and Kim et al. (2019) studied improvements in WDN reliability by deciding between valve placements, pipe rehabilitation, and adding parallel pipes.

3.3. Maintenance

Several major water outages have occurred in WDNs since valves were not maintained, so what could have been a routine pipe break turned into a catastrophic failure (Walski, 1993b). Almost all studies described in previous subsections have assumed that all isolation valves are operable. That is, they are normally open and can be fully closed to achieve a shutdown. There are numerous reasons why valves may be inoperable. In fact, they may happen to be paved over, and therefore difficult to locate, corroded to the extent that they cannot be operated, or difficult to access when vehicles have parked in proximity of the valve box. Other issues are the rounded operating nut and the valve box full of debris.

When a valve fails and is open, it means that the two adjacent

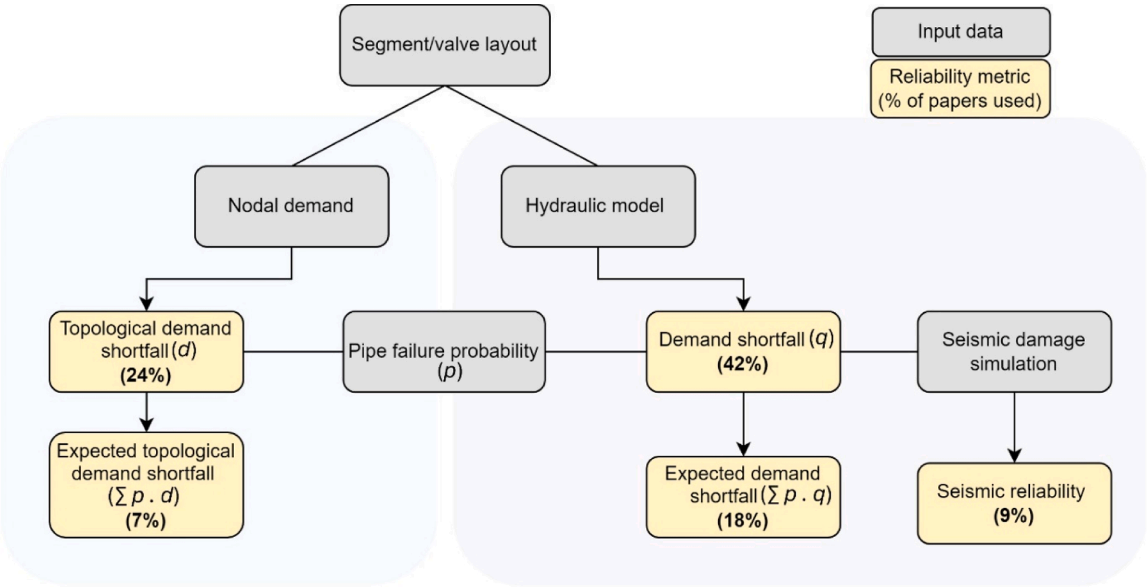


Fig. 5. The main types of reliability metrics and the input data required for each. The percentages show the ratio of papers that adopted that metric.

Table 3
Studies focused on the design and rehabilitation strategies of WDN based on the IVS from reviewed papers.

Simulation Tool	Decision variable	Objective Function	Tool	WDN Model	References
(Freeware)	Pipe replacement	Weighted demand shortfall	CPLEX	Segment/valve; Pipe/Node	Kao and Lee 2007
-	Valve placement	Maximum demand shortfall; Weighted average demand shortfall; Cost	MOGA	Segment/valve	Creaco et al. 2010b
-	Valve placement	Total demand shortfall; Number of valves	MOGA	Segment/valve	Giustolisi and Savic 2010
-	Valve placement	Maximum demand shortfall; Weighted average demand shortfall; Cost	MOGA	Segment/valve	Alvisi et al. 2011
-	Valve placement	Maximum demand shortfall	CLP(FD)	Segment/valve	Cattafi et al. 2011
-	Valve placement	Maximum demand shortfall	ASP	Segment/valve	Gavanelli et al. 2013
(Software with charge)	Pipe sizing	Cost; Maximum pressure deficit	MOGA	Segment/valve	Giustolisi et al. 2014
(Freeware)	Valve placement; Parallel pipe placement; pipe enlargement	Ratio of reliability to cost	Iterative algorithm	Segment/valve	Gupta et al. 2014b
-	Valve placement	Number of valves; demand shortfall; technical criteria	Multi-criteria decision	Segment/valve	Fontana and Morais 2017
(Freeware)	Valve placement	Number of additional valves; Demand shortfall	Monte Carlo simulation	Segment/valve	Choi et al. 2018
-	Valve placement	Demand shortfall	Single valve addition	-	Meng et al. 2019
(Freeware)	Valve placement or Pipe replacement	Demand shortfall; Cost	Minimum cut-set approach	Segment/valve	Kim et al. 2019
PDA (Freeware)	Phased valve placement	Max and weighted demand shortfall	GA	Segment/valve	Lee and Jung 2021
-	Additional Valve placement	Weighted demand shortfall; Cost	MOGA	Segment/valve	Yang et al. 2022
-	Additional Valve placement	Demand shortfall; Number of valves per segment	Graph theory	Segment/valve	Hernandez Hernandez and Ormsbee 2022

segments, connected by the valve, are now merged. Despite the significance of this issue, only a handful of studies have been undertaken to evaluate the consequences of valve failures and to suggest appropriate maintenance strategies (Table 4). These studies have addressed the challenge of scarce data concerning valve reliability, employing probabilistic (Trietsch and Vreeburg, 2005, Jun et al., 2008), optimal (Abdel-Mottaleb et al., 2022), or deterministic (Jun et al., 2007; Liu et al., 2017; Walski et al., 2019, Abdel-Mottaleb and Walski, 2020) failure scenarios. Notably, in all these studies, a valve is deemed to have failed if it remains open and cannot be closed, though cases are reported by water utilities in which isolation valves closed following segment isolations are unintentionally left closed, potentially resulting in locking. Moreover, the adverse impact of valve failure was measured based on its impact on the reliability of WDN in terms of number of affected customers and connections (Trietsch and Vreeburg, 2005; Jun et al., 2007; Jun et al., 2008), demand shortfall (Liu et al., 2017; Walski et al., 2019), segment importance (Abdel-Mottaleb and Walski, 2020), and social vulnerability (Abdel-Mottaleb et al., 2022). Notably, all these studies utilized the segment/valve topology.

Trietsch and Vreeburg (2005) and Jun et al. (2008) assumed a uniform failure probability for all valves and simulated a failure in each segment, taking into account the probability that the incident is limited to that segment or affects adjacent segments. Conversely, in the valve-by-valve failure analysis, the impact of the failure of each valve is calculated individually, and the valves are ranked accordingly. Jun et al. (2007) applied this approach considering the increase in the topological impact of segment isolation, whereas Abdel-Mottaleb and Walski (2020) evaluated the increase in the importance score of segments. Liu et al. (2017) and Walski et al. (2019), on the other hand, measured the impact of each valve failure by evaluating the increase in both topological and

Table 4
Studies focused on the valve failure and maintenance strategies from reviewed papers.

Hydraulic simulation	Methods	Performance Indicator	Valve Failure Model	WDN model	References
-	Practical engineering considerations	-	-	-	Walski, 1993b
-	Monte Carlo simulation Graph theory	Number of connections affected	Probabilistic	Segment/ valve	Trietsch and Vreeburg, 2005
-	Graph theory	Number of customers affected	Deterministic; Probabilistic	Segment/ valve	Jun et al. 2007
-	Graph theory	Number of customers affected	Deterministic	Segment/ valve	Jun et al. 2008
PDA (Software with charge)	Segment identification	Demand shortfall	Deterministic	Segment/ valve	Liu et al. 2017
PDA (Software with charge)	Segment identification	Demand shortfall	Deterministic	Segment/ valve	Walski et al. 2019
PDA (Software with charge)	Graph theory	Segments vulnerability and importance score	Deterministic	Segment/ valve	Abdel-Mottaleb and Walski 2020
PDA (Software with charge)	Graph theory, multi-objective optimization	Social vulnerability, Segment flow volume, Reachability impact	Optimal	Segment/ valve	Abdel-Mottaleb et al. 2022

hydraulic impacts of segment isolation through extended-period hydraulic simulations.

In a more recent study, Abdel-Mottaleb et al. (2022) employed the Gomory–Hu tree (Gomory and Hu, 1961) to analyse and identify segments unnecessarily isolated as a result of inoperable valves. This approach was then implemented in a multi-objective optimization to identify the most critical valves that maximize the social vulnerability, flow volume, and reachability impact of the segments.

As mentioned above, the performance indicators reported in Table 4 are based on reliability assessment measures. Therefore, the trade-off in reliability assessments between calculating the actual demand shortfall, including the pressure drops using a pressure-driven analysis, and its higher computational burden also exists for these analyses. At the same time, the computation expenses are even more critical due to the numerous evaluations needed for different valve failure scenarios. As a result, adopting a deterministic approach (valve-by-valve failures), in which the number of evaluations of the performance metric is equal to the number of valves, generally requires much lower computation resources in comparison to probabilistic methods where the possible combinations of valve failures can result into a much higher number of failure scenarios to evaluate. However, in real cases, several valves may be inoperable simultaneously, which cannot be accounted for by a deterministic approach.

4. On-field experiences

Every day, WDNs are built and operated around the world, with decisions made on valve placement and functioning. Valve placement has usually been based on engineering judgment and general rules of thumb, such as the N valve and N-1 valve rules. Though these approaches might be adequate for designing WDNs from scratch, problems often arise in existing networks due to their gradual evolution over time (Walski, 1994). Furthermore, the optimal valve placement largely depends on the customers' willingness to pay to prevent service interruptions during system shutdowns (Walski, 2011). In addition, valve maintenance and routine exercise programs play a crucial role in maintaining the reliability that is built into the system (Meng et al., 2019). Although water utilities are constantly dealing with these issues, there is a significant lack of readily available information on current on-field engineering practices concerning IVSs.

Traditionally, regulatory agencies have evaluated the adequacy of valves in terms of spacing between them. To the extent that the spacing of valves is an indicator of reliability, Walski (2011) analysed valve spacing at 13 water utilities, mostly in the United States, and found that the median value for valve spacing was 83 m (272 ft) which reflects the value that actual water utilities place on the trade-off between cost and the ability to isolate shutdowns. An exception to rules for valve placement is large transmission mains (roughly greater than 500 mm), where the cost of valves increases dramatically with size. Because of cost, these large pipes have greater spacing between valves. Plus, individual customers are generally not tapped into these segments. The valves connecting the transmission main to the distribution system tend to be the most critical ones in the system. Therefore, if one of those valves is inoperable, a minor pipe break could put the large transmission main out of service.

In order to capture the current situation in different countries, besides the academic standpoint, a survey was carried out to the managers of several water companies in Italy, Iran, Portugal, and the United States. Indeed, the idea is to bridge the gap between research and real-world applications, by reporting current engineering practice. In this regard, the water companies were directly contacted. After being informed about the purpose of the survey, their managers were invited to reply to the following six questions based on their on-field experience on the various networks that they managed in their action areas.:

- What is the IVS design strategy?
- What is the valve shutdown plan in case of pipe break?
- Which are the most important valves?
- Do you have a valve maintenance plan? If yes, what is the strategy?
- What is the valve failure rate?
- Which was the worst scenario associated with a single pipe break?

The results of the survey are summarised in Table 5. For the sake of privacy, for each country, the names of the water companies are omitted and designated as case study (CS) associated with a progressive number (if several). In the following sub-sections, case study engineering practices are grouped by country and on-field experiences are discussed in detail.

4.1. Italian case studies

Three water companies operating in Northern Italy and one in Central Italy were interviewed. For all of them, in case of a pipe break, mainly the goal is to be able to isolate the single pipe, in order to limit the unsupplied area, by adopting the N valve/N-1 valve rule design strategy, especially for the most recently installed pipes. In all four interviewed water companies, the worker has a tablet with a Web-GIS cartography of the whole WDN reporting all pipes and valves, with a special focus on those surrounding the area interested by the broken pipe, to define the proper shutdown plan. In case of faulty valves, the worker has to decide the nearest ones to close for the isolation of the pipe break. Only for one of the companies (ITCS3), a Web-GIS application

Table 5
On-field experiences survey summary from several-country water companies.

Country	Water company	IVS design strategy	Shutdown plan	Important valves	Maintenance plan	Valve failure rate
Italy	ITCS1	N valve	Web-GIS WDN map	All	Breakdown maintenance	20% - 30%
	ITCS2	N valve N-1 valve	Web-GIS WDN map	Larger diameter pipe	Breakdown maintenance	< 10%
	ITCS3	N valve	Web-GIS WDN map / app	Larger diameter pipe (450-1200mm)	Regularly	< 10%
	ITCS4	N valve	Web-GIS WDN map / Hydraulic simulations	DMA Borders Other relevant valves	Regularly	15%
Iran	IRCS1	N-1 valve N-2 valve	WDN map	Main assets / Larger diameter pipe	Regularly	20%
	IRCS2	N-1 valve N-2 valve	WDN map	Larger diameter pipe	Regularly	30%
Portugal	PCS1	N-1 valve	Web-GIS WDN map/ app	DMA Borders Other relevant valves	Systematic preventive maintenance	1% for WDN valves; 10% for connections valves
	PCS2	N valve	WDN map	All	Regularly(monthly)	10%
United States	USCS1	State Standards	WDN Map	All	Unavailable	Unavailable
	USCS2	State Standards	WDN Map	Transmission Mains	Unavailable	Unavailable

automatically indicates the nearest valves to close while considering potential valve failures. In addition, in case of pipe renewal, they insert a temporary bypass in order to avoid service disruption and then they also substitute the current valves. Another company (ITCS4) also employs hydraulic simulations to define shutdown procedures in more complex situations. These last two companies also perform regular maintenance of valves (especially those on the larger diameter pipes) by slowly exercising/operating them, preventing them from rusting. An additional benefit of this practice is that operators already know where to find the valves quickly, for fast interventions in emergency scenarios. On the other hand, due to a limited budget, the other two companies (ITCS1 and ITCS2) do not have a specific maintenance plan and simply operate breakdown maintenance. This forces water utility workers to report more numerous valve failures and to enlarge the network area to be isolated as a result of pipe breaks, therefore causing more frequent pressure-drop complaints during shutdowns. For these companies, end-user complaints also constitute the only way to detect valves unintentionally left closed. Furthermore, the absence of regular field inspection increases the probability of finding, in case of emergency, manhole covers covered with tar, and therefore unusable, as a result of street renewal interventions. Finally, in order to prevent large service disruptions as a result of a single pipe break (on a 200mm pipe and on a user connection pipe, respectively), the ITCS1 and ITCS2 companies had to repair the pipe break at nighttime after shutting off the nearest pumping station (reducing the area's pressure head). In a similar case, ITCS3 inserted a novel kind of valve on the broken pipe, to isolate a large diameter broken pipe without interrupting the supply. A similar strategy has been adopted by ITCS4 company, which has efficiently restored the water supply service in a short period by utilizing innovative valves and remote monitoring.

As for valve failure rate, the four water utilities interviewed report values ranging between <10% and 20%-30%.

4.2. *Iranian case studies*

Two water companies in North-central Iran were interviewed. Both companies employ either the N-1 or N-2 valve rules for valve placements, depending on the importance of the pipes and the area. In the event of a pipe break, these companies use the WDN maps to identify the valves that must be closed. All valves are coded, enabling an operator using the map to forward the code and location of the needed valves to field workers. If a valve is found to be inoperable, the nearest functional valve is manually located using the map. In terms of valve maintenance, IRCS1 company conducts regular exercises on valves based on their importance. Valves on main transmission lines, downstream of reservoirs, tanks, and pump stations are given the highest priority and are checked more frequently. Similarly, in IRCS2, the most critical valves are inspected every six months to a year. Historically, up to 70% of the valves in IRCS1 were either inoperable or paved over, creating substantial operational challenges. For instance, there was an incident in 2005, where after eight valves were inoperable for isolating a pipe break, it was decided to close the valve on the main tank, which was also found defective. The resulting situation forced complete drainage of the tank before repairing and replacement of the pipe and the nine faulty valves. However, maintenance and renewal projects in IRCS1 over the past decade have reduced the number of inoperable valves to below 20%. For IRCS2, this number is up to 30%.

4.3. *Portuguese case studies*

Two water companies in the area of Lisbon and Tagus Valley were contacted to participate in the survey to understand current practices with regard to isolation valves. Water company PCS1 uses a multivariable analysis with three main factors for isolation valves design strategy: N-1 valves for each node; hydraulic modulation to guarantee flow and pressure; and a minimum number of customers affected for each shutdown area. To implement the valve shutdown plan in case of a pipe break, the valves are first analysed using an on-line GIS WDN system. This analysis, supported by hydraulic simulation models, will help to identify: 1) valves to be closed; 2) valves to be opened to guarantee the flow and pressure in the bordering areas of the shutdown distribution network area; 3) number of customers who will be affected by the water supply interruption; 4) carry out valve maneuvers; 5) inform by SMS all customers that will be affected by the water shutdown and the period of the works. To guarantee distribution, a bypass may be implemented (only for the implementation of the bypass the service is temporarily suspended). The valves considered important are: from DMA borders; valves that shut down more than "n" customer connections; and in larger diameter pipes (450-1200mm). There is a preventive maintenance policy for valves with spare parts and components and a systematic maneuver plan for other valves to guarantee functionality. For wedge valves below DN 300 that do not require maintenance as they do not have components, a preventive maneuver plan is carried out. To ensure the safety of infrastructures, an assessment of protection and safety bodies and appropriate methodologies for the automated opening and closing of valves is developed. The implementation of these policies over the years has resulted in a very low failure rate. Company PCS2 has a smaller budget, so some difficulties are experienced. They have a WDN map that serves to locate the problem and define how to proceed. When events happen, depending on the area, for example the looped part of the network, they can define other ways of continuing to deliver the service. If this is not possible, the network is sectioned, and the supply is cut off for the shortest possible time to carry out repairs, regardless of pipe diameter. The company has a monthly maintenance plan, but sometimes it is not fully implemented. This means that the action is often curative only to carry out breakdown maintenance, thus increasing the number of complaints and resulting in a higher failure rate.

4.4. United States case studies

USCS1 is a large investor-owned water company that owns water systems across the US. As part of their "Best Practices Guidelines", they require that planning studies for their individual systems include a segmentation and criticality analysis to identify valving inadequacies as long as sufficient data are available to conduct the analysis.

USCS2 is a large city that purchases water wholesale from a larger supplier. A single break on the main connecting the two systems put tens of thousands of customers out of water for more than a day.

A good way to look at US systems in terms of valving is to consider the design standards, usually at the state level. Many are based on the spacing criteria from the Ten State Standards with the general introductory sentence, "enough valves shall be provided on water mains to minimize inconvenience and sanitary hazards will be minimized during repairs."

Each state has its own version of this wording. Texas Commission on Environmental Quality (2019) states, "The system shall be provided with sufficient valves and blowoffs so that necessary repairs can be made without undue interruption of service over any considerable area and for flushing the system. The engineering report shall establish criteria for this design." The engineer is responsible for design criteria.

The wording in Washington State (2020) says, "Designers should place enough valves to minimize the number of customers out of service when the water system needs to isolate a location for maintenance, repair, replacement, or additions."

New Jersey (2020) is one of the few that actually specifies valve location with consideration of the number of valves at an intersection, "Water distribution mains shall be equipped with sufficient numbers of valves to minimize service interruption and safety hazards during repairs. The appropriate number of valves at each intersection shall be determined using an N-1 formula (for example at a four-way intersection, a minimum of three valves is required. Straight pipes such as transmission mains shall be equipped with valves at intervals of a minimum of 2500 ft (762 m). The Department shall approve deviations from the minimum valve interval for larger transmission line if justification therefore is provided but in no case shall the interval between valves exceed one mile (1609 m)."

These standards have migrated down to individual water utilities. For example, Albemarle County Service Authority (2022) ACSA requires "Three (3) valves are required at crosses on systems, two (2) valves at tees; the valves are to be placed on the smaller lines at each cross and tee location unless otherwise approved by the ACSA. In other areas gate valves will be required every 1000 feet, except as may otherwise be approved by the ACSA."

Another approach to valving is establishing the maximum number of valves that must be closed to achieve a shutdown in a system. As the number of valves needed to achieve a shutdown increases, the chance that one of them will be inoperable also increases.

5. Current issues and perspectives

The primary step in any investigation about IVSs is to properly model valve devices in WDN layouts and to identify associated segments. For this purpose, efficient methods are proposed in the literature. However, in many cases, the main challenge in modeling the IVS of real-world WDNs is access to updated models or maps that accurately represent the location of all valves and their operability. This issue seems to have narrowed down the research with case studies featuring real IVSs. In this regard, access to information on real WDNs with actual valve distributions, such as the publicly available database by Ormsbee et al. (2022), can boost the research on the topic. Yet, more on-field studies are needed to illuminate the actual challenges and practices regarding the management, design, and maintenance of IVSs in real-world WDNs.

Furthermore, the analysis of the literature carried out here highlighted that there is no universally accepted metric/parameter for performing the reliability analysis of WDN against component failures, even though, in most cases, it is based on demand shortfalls caused by segment isolations. Due to challenges associated with the pressure-driven hydraulic simulations to obtain both topological and hydraulic demand shortfalls, namely computational burden and unavailability of well-calibrated hydraulic models, the reliability assessment based on WDN topological analysis is of high interest. The topological measures, mainly utilizing graph theory tools, offer quick preliminary insights into network reliability. However, they can underestimate the vulnerability of segments or misjudge their criticality by neglecting the hydraulic demand shortfall component. Besides, the robustness of these topological measures for reliability assessment and IVS layout analysis needs to be evaluated over diverse cases with different topologies.

The trade-off between accuracy and computational expense in reliability assessment needs further investigation. Alternative methods and their combinations with segment analysis can be explored to find a suitable balance. For example, clustering the segment/valve topology, as in the work of Creaco et al. (2023), can allow to address the problem by separately focusing on smaller, more manageable sub-areas/models.

It is worth noting that a standard test library of case studies is required to understand the actual difference between the reliability metrics introduced in the scientific literature and highlight their strength and weaknesses for different tasks (i.e., design, criticality analysis, and maintenance) and in different contexts (i.e., WDN-data / computational resources availability). Analysis of some of the metrics against each other for IVS design can be found in the literature (e.g., Creaco et al., 2012; Mottahedin et al., 2024b). Future investigations are called for in this context.

Furthermore, as the risk related to demand shortfall assessment is given by the product of failure probability, exposure, and vulnerability, incorporating a more robust model for the failure probability of pipes can significantly impact the evaluation of segment isolation risk. For instance, a segment with a relatively low demand shortfall can become highly critical if it features a high rate of failure frequency. Yet, the proposed reliability measures have often ignored the failure probability or simplified it using surrogate metrics, like pipe length. Another common simplification is considering the same level of exposure and vulnerability, i.e., the same level of damage, to demand shortfall across the network. This assumption ignores that supply disruption to more critical user nodes, such as hospitals, schools, etc., can result in much higher risk than other areas with the same demand. Therefore, it is necessary to perform a separate analysis of these locally critical nodes under isolation scenarios and consider the possibility of maintaining their supply through multiple paths. Furthermore, for a more detailed reliability analysis, other complementary weighting strategies may be used, by assigning to segments also a criticality score according to the impact on population health and economic/social prosperity of their isolation, like a coefficient of exposure of the affected area to be derived from urbanistic/logistic analysis.

The mentioned issues also hold for IVS design since, typically, the performance of design solutions for valve placements is evaluated by reliability measures. In addition, studies on IVS design often neglect the dynamic behavior of WDNs, while assuming the same settings for network components like pumps and control valves during failure incidents. The potential of changes in the operation of such components under abnormal conditions can significantly affect the WDN performance for good or ill. Therefore, dynamic analysis of the WDN, including components with adjustable settings, may improve the decision on IVS design. However, as this analysis increases computational costs, further investigation is needed to assess its profitability across various scenarios.

The optimal design of IVSs regarding WDN reliability and cost of valve placement is also affected by the pipe diameter design of the WDN. Suppose the difference in cost of valve placement on the different pipes of the WDN would be negligible due to the narrow range of pipe diameters. In that case, the most decisive factor in the IVSs' performance is the number of valves. Accordingly, when the valve density is higher than a certain threshold (e.g., 0.8 valve per pipe), the improvement provided by an optimized valve layout arrangement is likely small (Hwang and Lansey, 2021). In other cases, where the difference in cost of valve placement on the different pipes of the WDN is significant, valve location optimization can result in notable improvements even among the different combinations of the N-1 valve rule (Mottahedin et al., 2024b).

Moreover, in the studies on IVS design, the relation between the cost of valve placement and the impact of valve failure has yet to be addressed. Intuitively, the effect of valve failure decreases as the redundancy in valve placements, and therefore valve cost, increases. However, further investigation is needed to take into account the reliability of IVS itself in the valve placement. Indeed, the on-field surveys presented in this study show that utilities may prefer IVS layouts such as the N valve rule to methods based on optimal valve placement cost since they can be more resilient to valve failures where routine maintenance of the valves is mainly dismissed. A higher number of valves increases investment and maintenance costs but reduces the negative effect of failures. In the N valve rule, the IVS can also be analyzed in the conventional pipe/node topology, which reduces the complications of the dual segment/valve topology modeling. These points may explain utilities' potential preference for employing N/N-1 valve placements if financial constraints allow to adopt these strategies characterised by higher investment costs.

On the other hand, an optimised valve layout (with a lower number of valves optimally placed) even if resulting in lower initial costs, may call for a more detailed, regular, and focused maintenance programme (Mottahedin et al., 2024a). For a comprehensive design decision, the impact of different combinations of valve failure rates on reliability and the cost of alternative valve maintenance programs on the total cost must be considered. In this regard, these two opposite design paradigms should be better investigated, as well as, the trade-off between cost and reliability, also because this may be affected by site-specific needs and conditions (water utilities policy, spatial demand distribution, WDN topology).

The primary paradigm of the reviewed studies on valve maintenance is to evaluate the risk of losing reliability for valve failure scenarios to find the most critical valves. In all of those studies, valve failure refers to valves that are stuck open and cannot be closed, and other types of inoperable valves, such as those that are stuck closed or cannot be located, are not addressed. Although considering a single valve failure at a time can indicate some critical valves by relatively lower computational resources, it is far from the on-field reality where multiple valves may be inoperable simultaneously. This highlights the need for frameworks capable of considering the uncertainty in the inoperable valves' location and probability. Moreover, similarly to reliability measures, the difference between the proposed metrics for evaluating the impact of valve failures needs to be thoroughly analyzed. For this purpose, Mottahedin et al. (2024a), while proposing a novel isolation valve maintenance strategy, suggested a framework based on generating random multiple valve failure scenarios that can be beneficial for assessing each metric to measure the impact of valve failures.

The lack of comprehensive plans for valve maintenance observed from on-field surveys suggests a consequential benefit in exploring maintenance strategies that water utilities can adopt to decrease the likelihood of valve failures. For this purpose, besides identifying the valve failures with the highest impact on WDN reliability, it would be beneficial to develop predictive models for valve failures similar to those suggested in the scientific literature for pipe failures. In this regard, once again the availability of historical real-case data is of crucial importance, and the adoption of machine learning techniques for exploiting this information and arranging forecasting tools may be promising in easing/enhancing effective maintenance activities for a better resources' allocation (staff, tools, and money).

6. Conclusions

The issues of isolation valves and segments in water distribution networks have been deeply analysed in the scientific literature over the last three decades.

Overall, the review of the state of the art has pointed out:

1- Efficient and effective algorithms exist for the identification of segments and for the analysis of network performance during segment isolation scenarios.
2- Though attracting the interest of numerous researchers worldwide, the optimal design of the system of isolation valves is an issue of little interest to water utilities, since they almost always resort to simple placement rules, such as those aimed at installing valves on all (or all but one) pipes connected to each network node, corresponding to each road intersection. Though these rules may incur in larger investments, they offer the advantage of easily tracing back to the valves to shut off for pipe isolation. The advantage of employing optimal IVS design is especially significant in scenarios with tight budget constraints that limit the number of valves to be installed but it gradually vanishes as the number of valves increases and the IVS layout approaches the N valve rule.
3- As valves tend to break, if not frequently operated, the issue of valve maintenance is of primary importance. However, it appears that some water utilities choose not to abide by the wise saying "prevention is better than cure", based on economic constraints. Indeed, they prefer to put off the issue of potential valve failure to the time the valve needs to be operated for segment isolation. The presence of few scientific works on selection criteria for valve maintenance calls for additional investigations in the scientific community.

CRediT authorship contribution statement

Amirabbas Mottahedin: Writing – original draft, Methodology, Investigation, Formal analysis. **Carlo Giudicianni:** Writing – review & editing, Methodology, Formal analysis. **Fabio Di Nunno:** Writing – review & editing, Investigation. **Francesco Granata:** Writing – review & editing, Investigation. **Maria Cunha:** Writing – review & editing, Supervision, Investigation. **Thomas Walski:** Writing – review & editing, Methodology, Investigation. **Enrico Creaco:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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Supplementary materials

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